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A PROCEDURE FOR THE DESIGN OF COMPLEX DISTORTION SCREEN PATTERNS FOR PRODUCING SPECIFIED STEADY-STATE TOTAL PRESSURE PROFILES AT THE INLET OF TURBINE ENGINES

B. W. Overall

ARO, Inc.

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ENGINE TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The work reported herein was performed at the request of the Aeronautical Systems Division (ASD)(YFT), Air Force Systems Command (AFSC), Wright-Patterson Air Force Base, Ohio, under Program Element 64209F, System 328A.

The results of this investigation were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under contract F40600-72-C-0003. The tests were conducted in Propulsion Development Test Cell (T-4) of the Engine Test Facility (ETF) from February 17 to April 22, 1971, under ARO Project No. RD0125. The manuscript was submitted for publication on November 12, 1971.

This technical report has been reviewed and is approved.

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ABSTRACT

A technique was developed for the design of distortion screens which will produce a specified steady-state total pressure profile at the inlet of a turbine engine. The design technique is discussed, and sample results of its application are presented. The influence of the distortion screens on wall static pressure upstream of distortion screens is discussed, and the total pressure distortion from a 180-deg solid plate is presented. Measured total pressure loss is presented for screens of various porosity.

CONTENTS

ILLUSTRATIONS

TABLE

APPENDIX

NOMENCLATURE

A	Area, in.^{2}
AF	Flow area, in.^{2}
Cd	Total pressure loss coefficient
CF	Venturi flow coefficient
CP	Specific heat at constant pressure, Btu/lbm-°R
d	Flow station upstream of distortion screen
gc	Dimensional constant, 32.174 lbm-ft/lbf-sec^2
M	Mach number
P	Total pressure, psia
PS	Static pressure, psi
PSFN	Normalized static pressure function
q	Dynamic pressure, psia

R	Gas constant for air, 53.34 ft-lbf/lbm-°R
RNI2	Reynolds number index at station 2
S	Screen porosity
T	Total temperature, °R
V	Velocity, ft/sec
W	Mass flow rate, lbm/sec
γ	Ratio of specific heats
σ	Standard deviation

POSTSCRIPTS

00	Venturi inlet station
1N, ID, 2, etc	Instrumentation stations
A	Air
AVG	Average
c	Proposed screen section change
D	Inlet duct
i	Individual screen section
MAX	Maximum
MIN	Minimum
X	Plane of minimum area of screen

SECTION I
INTRODUCTION

The recent increase of emphasis on the effects of inlet total pressure distortion on turbine engine stability and performance has resulted in a major effort by ground test facilities to duplicate the inlet total pressure profiles encountered during operation of engines over the aircraft flight envelope. The most widely accepted approach to producing the distortion patterns has been the use of complex screen assemblies of various porosity screens. The development of these screen patterns in the past has been a "cut and try" procedure requiring several iterations to produce a desired total pressure profile. Therefore, a systematic procedure for the design of distortion screens was developed at the Engine Test Facility in an effort to minimize the number of iterations required to produce a desired total pressure profile at the inlet of a turbine engine for given conditions of altitude, Mach number, and total airflow.

The objective of the investigation reported herein was to develop a method for the design of distortion screens that would produce specified total pressure profiles in a flow annulus downstream of the screen plane. The specified total pressure levels are duplicated on a point-by-point basis for a given simulated flight condition and airflow. The design procedure was developed using specified and measured total pressure values at 48 discrete locations in the flow annulus.

This report presents the design technique which was developed and assembles the information which is required to design a complex screen pattern. The effects of distortion screens on wall static pressures upstream of the screens are also discussed. Measured total pressure loss data for screens of various porosity are included. The total pressure distortion produced by a 180-deg solid plate is presented.

SECTION II
APPARATUS

2.1 TEST ARTICLE

A simulated engine inlet duct and front frame configuration (Fig. 1) was utilized as a turbine engine inlet simulator. The distortion screen support assembly (Fig. 2) was an integral part of the engine inlet duct.

The distortion screen configuration was a composite of several sections of different porosity (percent open area) screens. The individual screen sections were single layers of uniform mesh, wire cloth which was woven from circular cross-section wire strands. The wire cloth was fabricated from 7074 stainless steel wire and was obtained from commercial sources. The screen sections were mounted (safety wired) to a backing grid of 1-in. center-to-center 0.125-in.-diam wire that covered the entire duct area. A photograph of a typical distortion screen configuration is presented in Fig. 3.

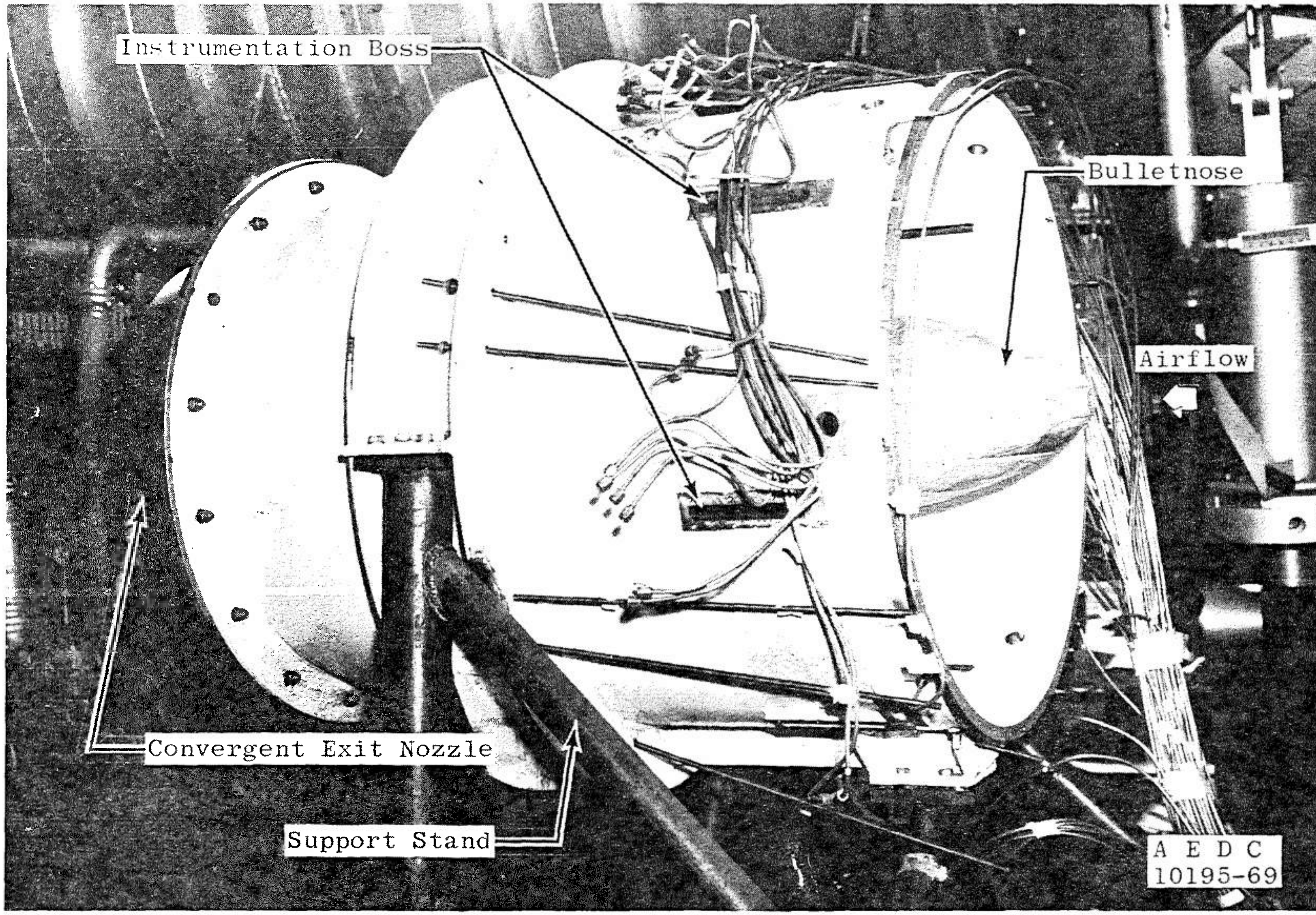


Fig. 1 Engine Inlet Simulator

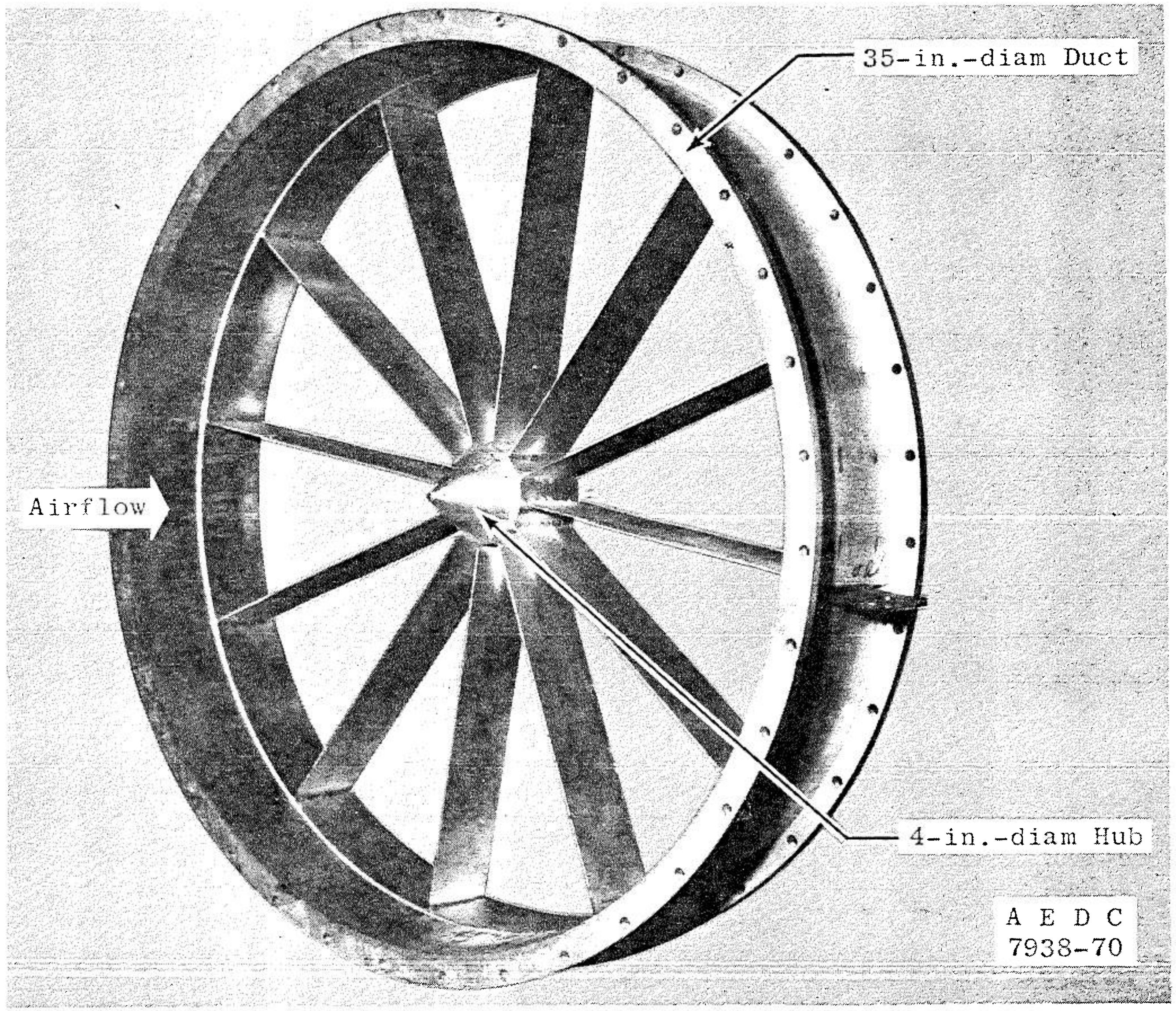
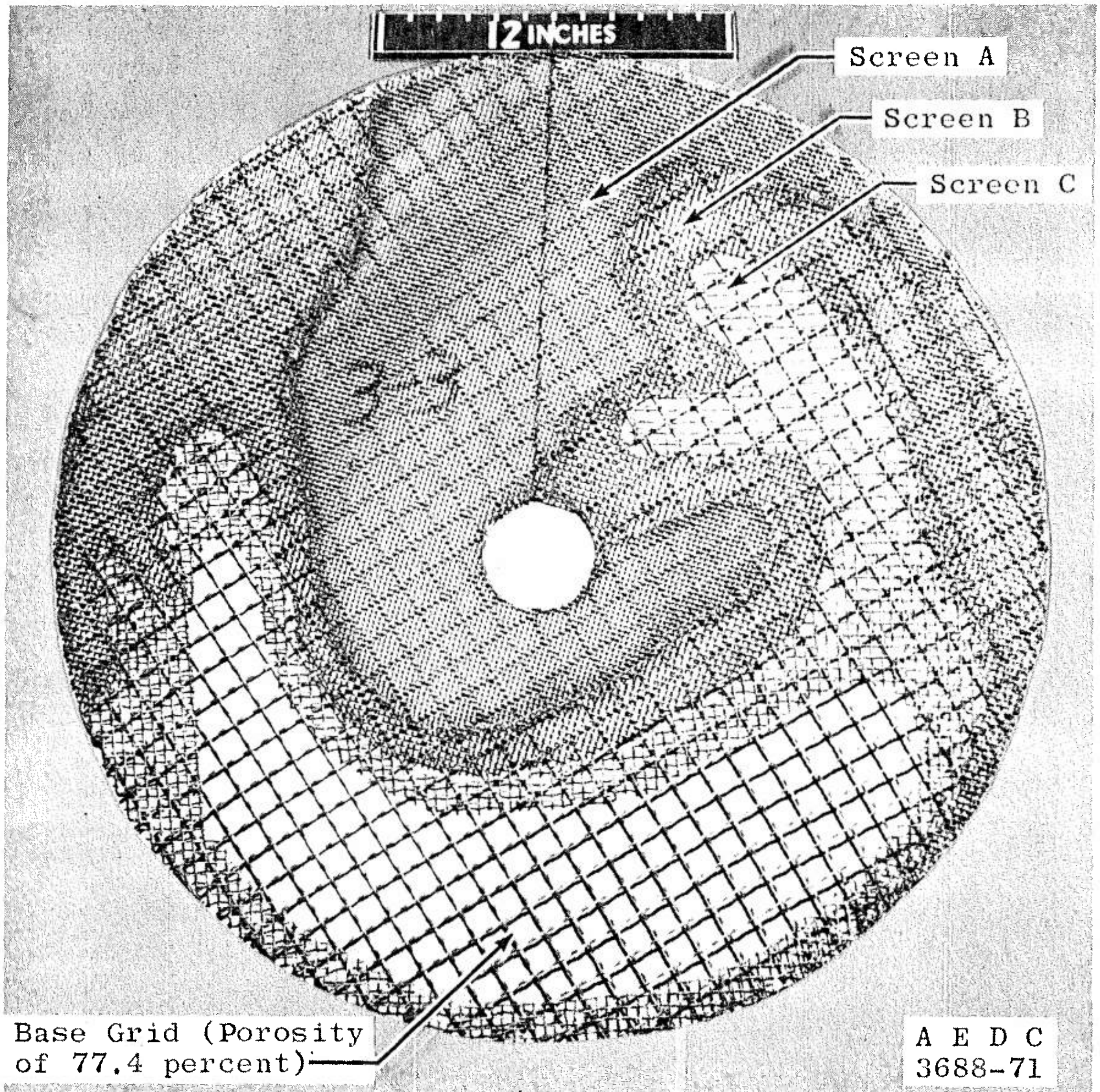


Fig. 2 Distortion Screen Support Assembly



Screen	Percent Porosity	Mesh, Wires per in.	Wire Diameter, in.
A	42.8	5.5	0.063
B	51.2	4.5	0.063
C	71.0	2.5	0.063
Base Grid	77.4	1.0	0.125

Fig. 3 Typical Distortion Screen (View Looking Downstream)

2.2 INSTALLATION

The 34.8-in.-diam inlet duct, distortion screen, and engine inlet simulator were installed in Propulsion Development Test Cell (T-4) as shown in Fig. 4. The screen support assembly (Fig. 2) formed a section of the inlet ducting. A bellmouth inlet was installed upstream of the plane of the distortion screen, and a turbojet engine inlet simulator was installed downstream of the distortion screen. The engine inlet simulator contained an instrumentation section consisting of eight, six-probe, total pressure rakes. The forward tips of the total pressure probes were in a plane located 25 in. downstream of the distortion screen. At the instrumentation plane, the duct and centerbody formed a flow annulus with inner and outer diameters of 11.0 and 34.8 in., respectively. Airflow was measured using a critical-flow venturi located approximately 45 ft upstream of the bellmouth inlet. A 5-ft-diam collector duct was located downstream of the inlet simulator. A detailed description of the T-4 test cell is given in Ref. 1.

2.3 INSTRUMENTATION

Aerodynamic pressure and temperature measurements were made at the stations shown in Fig. 5. Diagrams showing the number and type of instrumentation at each station are shown in Fig. 6.

Steady-state pressures were measured with strain-gage-type transducers, and temperatures were measured with copper-constantan thermocouples. The voltage outputs of the transducers and thermocouples were recorded on magnetic tape from high-speed analog-to-digital converters and converted to engineering units by an electronic digital computer. Selected channels of pressure and temperature were displayed in the control room for observation during operation.

The instrumentation ranges, recording methods, and posttest estimates of measurement uncertainty are presented in Table I.

2.4 CALIBRATION

All transducer and system calibrations performed during this test are traceable to the National Bureau of Standards (NBS). Each link in the traceability chain back to the NBS is maintained and documented by the AEDC Standards Laboratory (Ref. 2).

The aerodynamic pressure measurement transducers utilized in the Automatic Multiple Pressure Scanning (AMPS) System (Table I) were in-place calibrated before and after each test period by applying multiple pressure levels within the pressure range from 1.5 to 15.0 psia. Each applied pressure level was measured with a pressure measuring device calibrated in the Standards Laboratory.

All thermocouples were fabricated from wire conforming to Instrument Society of America Specifications. Before and after each test period, known millivolt levels were applied to each temperature recording system, and the corresponding temperature equivalents were obtained from 150°F reference tables based on the NBS temperature

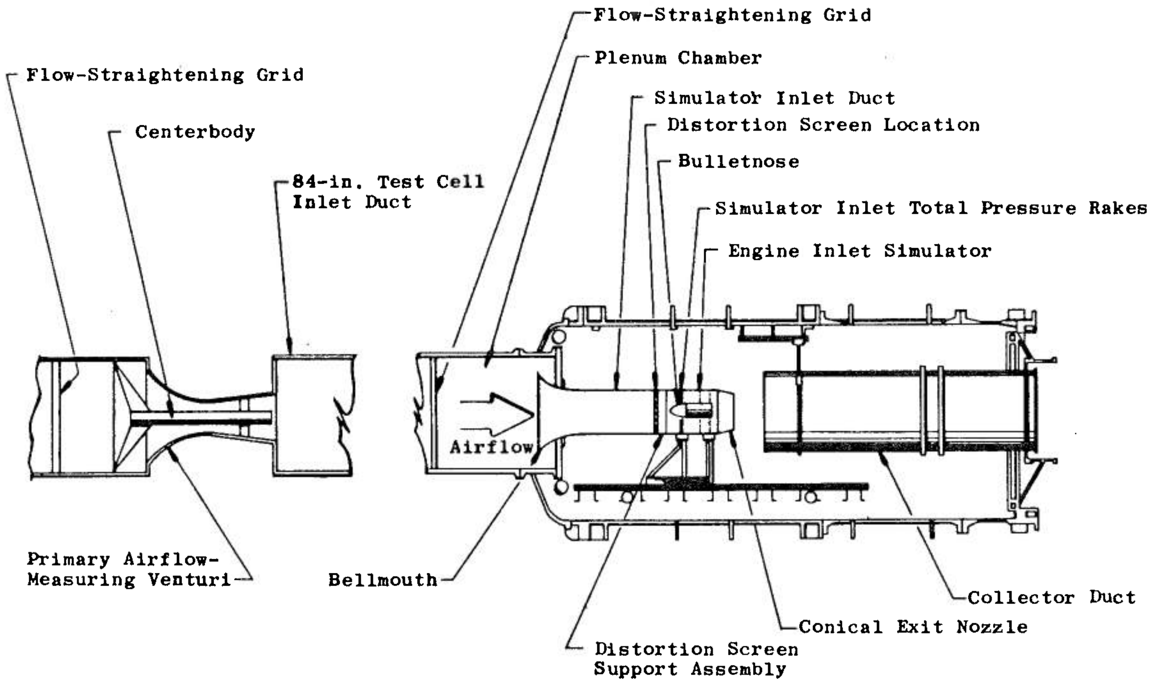
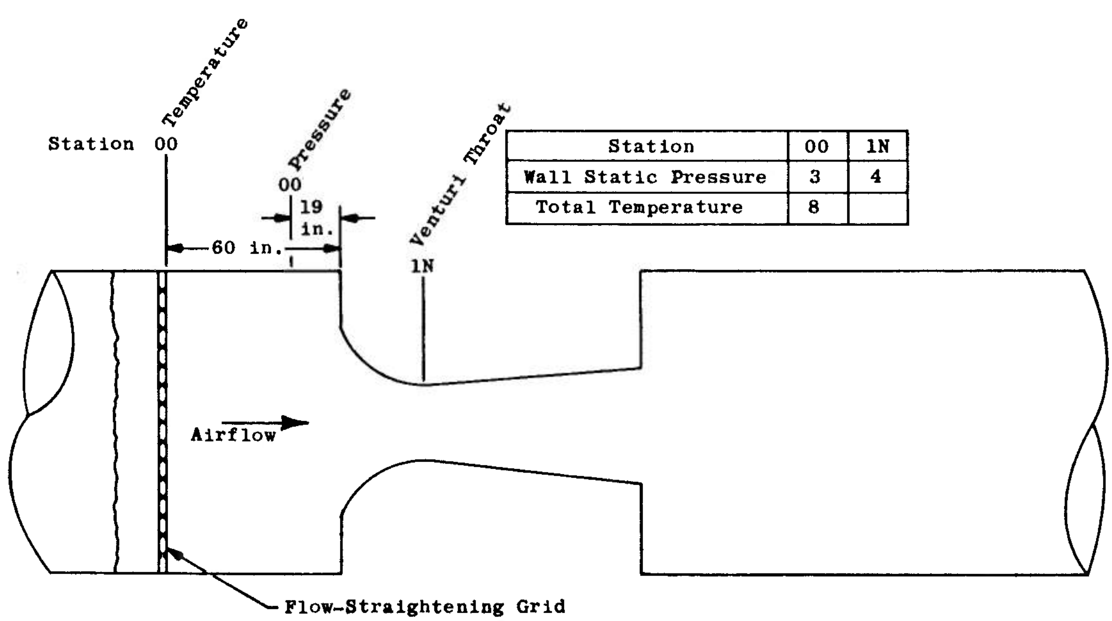
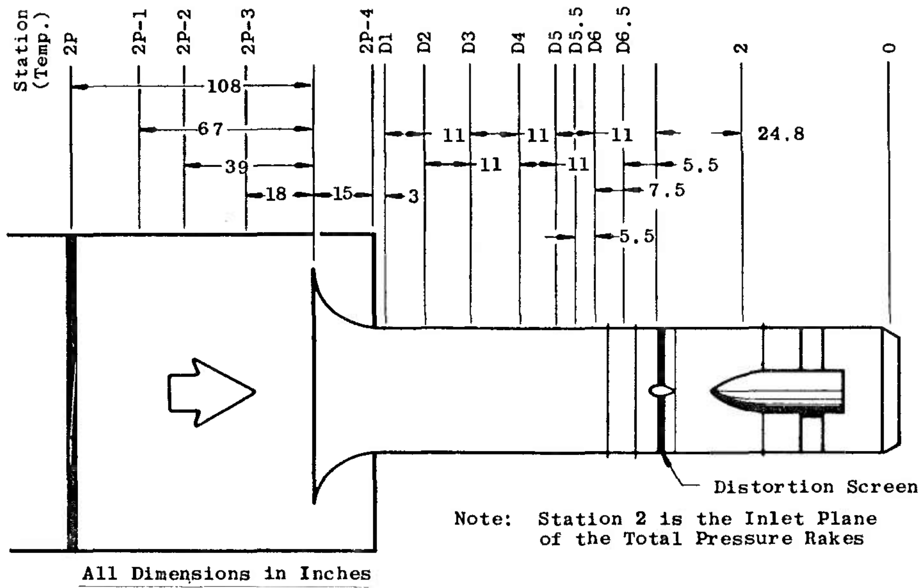


Fig. 4 Installation of the Distortion Screen and Engine Inlet Simulator in Propulsion Development Test Cell (T-4)



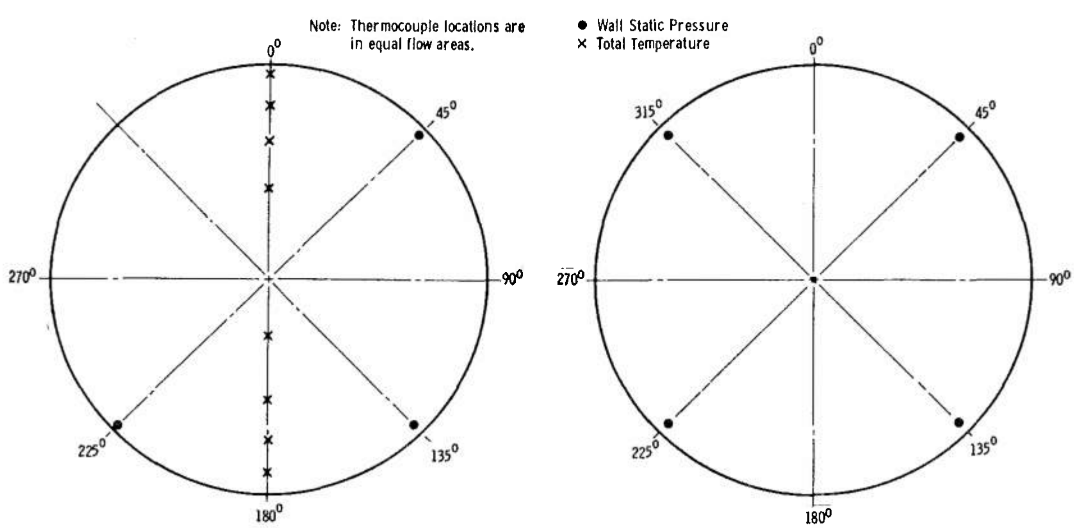
Station	00	1N
Wall Static Pressure	3	4
Total Temperature	8	

a. Airflow Measuring Venturi
Fig. 5 Instrumentation Station Locations



Station	2P	D1	D2	D3	D4	D5	D5.5	D6	D6.5	2	0
Wall Static Pressure	6	4	4	4	4	4	4	4	4	4	2
Total Temperature	8	-			-	-	-	-	-	-	-
Steady-State Total Pressure	-	-			-	-	-	-	-	48	-

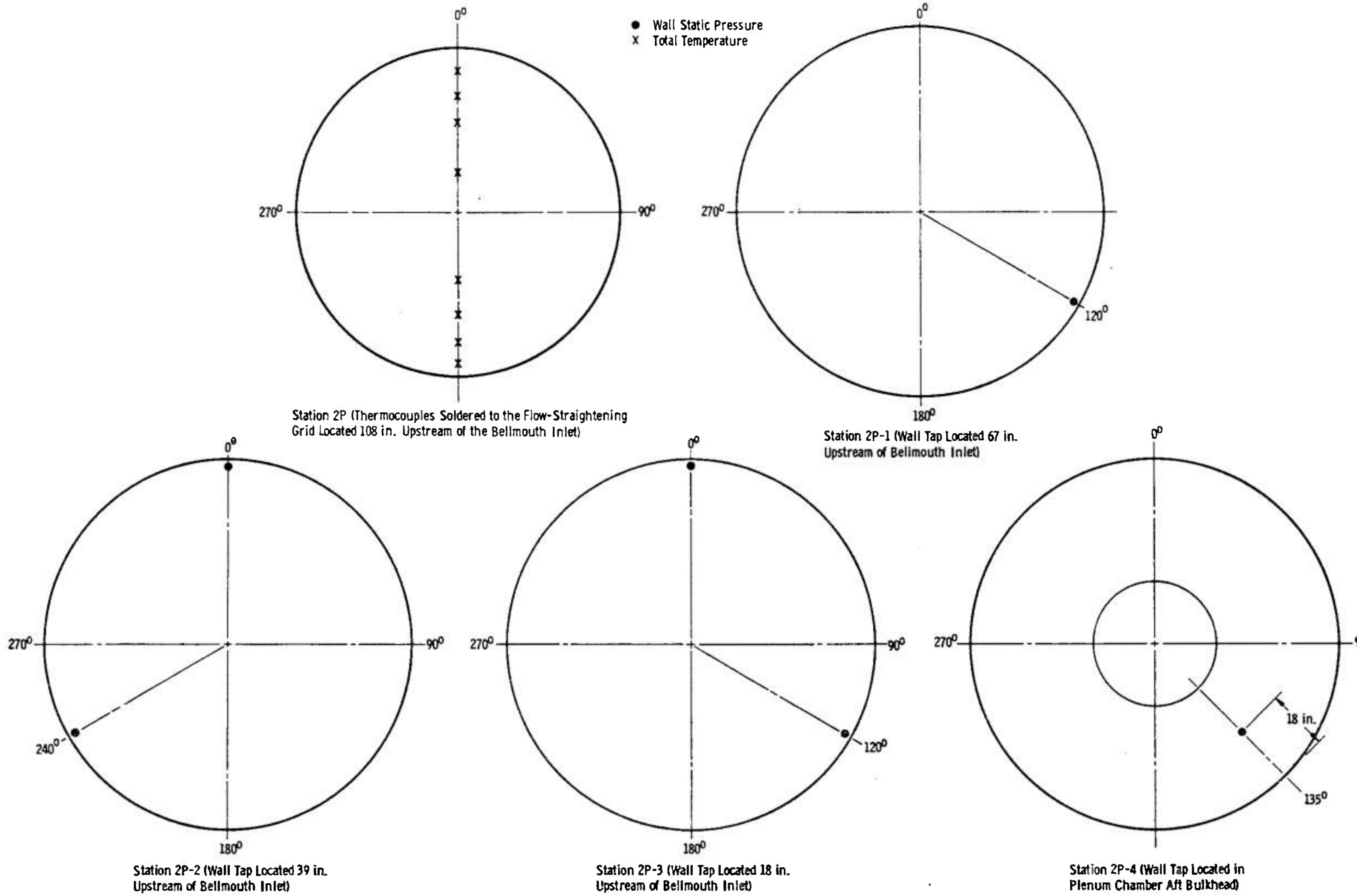
b. Plenum and Engine Inlet Simulator
Fig. 5 Concluded



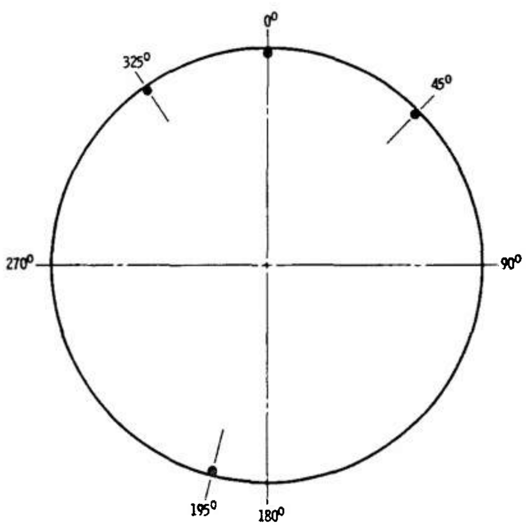
Station 00, Venturi Inlet (Temperature Thermocouples Soldered to the Honeycomb Grid Located 60 in. Upstream of the Venturi Inlet; Pressure Taps Located 19 in. Upstream of Venturi Inlet)

Station 1N Venturi Throat

a. Airflow Measuring Venturi
Fig. 6 Instrumentation Details (Looking Upstream)

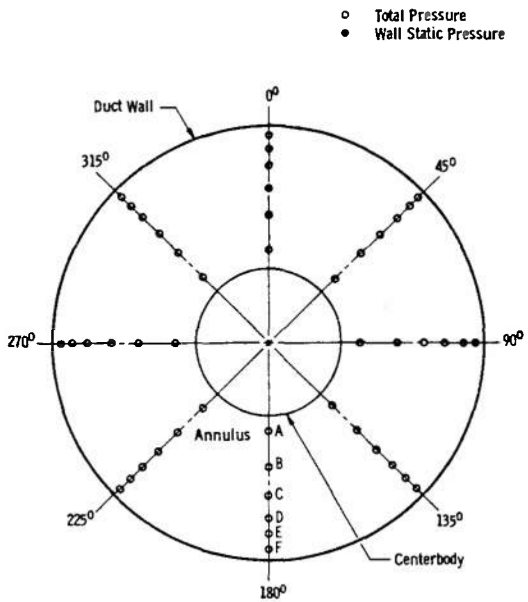


b. Test Cell Inlet Plenum Chamber
Fig. 6 Continued



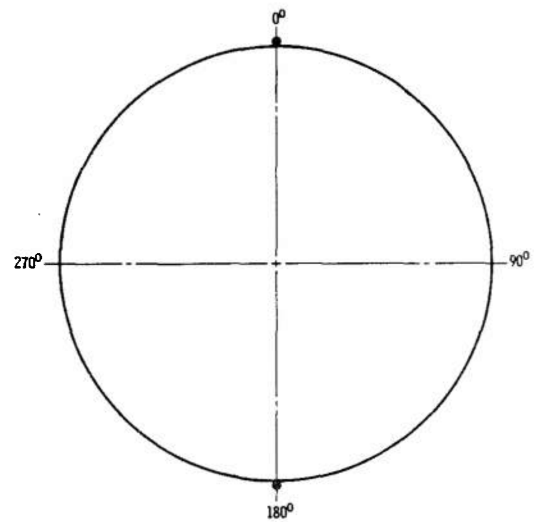
Station	D1	D2	D3	D4	D5	D5.5	D6	D6.5
Distance Upstream of Distortion Screen, in.	68.0	57.0	46.0	35.0	24.0	18.5	13.0	5.5

c. Simulator Inlet Duct



Note: Total pressure probes are located at the area center of equal annulus areas (A through F).

d. Station 2, Simulated Engine Inlet



(Located on the Outer Surface of the Simulator Nozzle 2 in. Upstream of the Exit Plane)

e. Station 0, Exit Cone

Fig. 6 Concluded

TABLE I
INSTRUMENTATION SUMMARY AND MEASUREMENT UNCERTAINTIES

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT* Precision Index (S) Percent of Reading	Precision Index (S) Unit of Measurement	Precision Index (S) Degree of Freedom	Bias (B) Percent of Reading	Bias (B) Unit of Measurement	Uncertainty $\pm(B + t_{95}S)$ Percent of Reading	Uncertainty $\pm(B + t_{95}S)$ Unit of Measurement	Range	Type of Measuring Device	Type of Recording Device	Method of System Calibration
Venturi Inlet Static Pressure (PS00)	±0.06	---	36	±0.40	---	±0.52	---	3.0 to 12.0 psia	Bonded Strain-Gage-Type Pressure Transducers	Automatic Multiple Pressure Scanning System onto Sequential Sampling; Millivolt-to-Digital Converter, and Magnetic Tape Storage Data Acquisition System	In-Place Application of Multiple Pressure Levels Measured with a Pressure Measuring Device Calibrated in the Standards Laboratory
Venturi Throat Static Pressure (PS1N)	±0.12	---	36	±0.24	---	±0.48	---	1.5 to 10.0 psia	↓	↓	↓
Plenum Chamber Static Pressure (PS2P)	±0.14	---	36	±0.23	---	±0.51	---	1.7 to 12.0 psia	↓	↓	↓
Inlet Duct Wall Static Pressure (PS2)	±0.13	---	36	±0.24	---	±0.50	---	1.7 to 10.0 psia	↓	↓	↓
Simulator Inlet Total Pressure (P2)	±0.13	---	36	±0.20	---	±0.46	---	1.7 to 10.0 psia	↓	↓	↓
Test Cell Pressure (PCELL)	±0.13	---	36	±0.25	---	±0.51	---	1.1 to 10.0 psia	↓	↓	↓
Simulator Exit Cone Static Pressure (PSO)	±0.13	---	36	±0.25	---	±0.51	---	1.1 to 10.0 psia	↓	↓	↓
Inlet Duct Static Pressure (PSD)	±0.15	---	36	±0.25	---	±0.55	---	1.7 to 10.0 psia	↓	↓	↓
Venturi Inlet Total Temperature (T00)	---	±0.25°F	95	---	±1.8°F	---	±2.3°F	-10 to +200°F	Copper-Constantan Temperature Transducers	Sequential Sampling, Millivolt-to-Digital Converter, and Magnetic Tape Storage Data Acquisition System	Millivolt Substitution Based on the NBS Temperature versus Millivolt Tables
				±(1.3°F + 0.25%)		±(1.8°F + 0.25%)		+200 to +320°F	↓	↓	↓
Plenum Chamber Total Temperature (T2P)	---	±0.25°F	95	---	±1.8°F	---	±2.3°F	-10 to +200°F	↓	↓	↓
				±(1.3°F + 0.25%)		±(1.8°F + 0.25%)		+200 to +320°F	↓	↓	↓

*Reference: CPIA No. 180. "ICRPG Handbook for Estimating the Uncertainty in Measurements made with Liquid Propellant Rocket Engine Systems." April 30, 1969.

versus millivolt tables. Nonlinearity in the thermocouple characteristics were accounted for in the data reduction program.

SECTION III
PROCEDURE

The design technique for developing a complex screen pattern is a systematic procedure that is applicable for any specified total pressure profile. The basic requirements that must be specified are the individual total pressure values and their locations at the simulated engine inlet plane, the limits within which each pressure value must be reproduced (tolerance limit), the flight condition to be simulated at the inlet plane, and the airflow. The basic steps in the procedure are defined in the following discussion.

The specified total pressure values defined at the simulated engine inlet are transposed to equivalent locations (comparable flow area for each pressure value) at the plane of the distortion screen. An isobar map at the plane of the distortion screen is generated for the specified total pressure values (see Appendix I).

The individual screen section shapes are described by using selected isobars from the pressure map as screen boundaries. The isobar selection technique provides a means of selecting the minimum number of individual screen sections that are required for any specified pattern.

The ideal porosity for each screen section is calculated and actual screens are selected to conform as closely as possible to the ideal.

The initial screen configuration is fabricated from the patterns defined by the isobar map using the selected screen size.

A test run is conducted with the initial screen configuration at the specified simulated flight condition and airflow.

The arithmetic averages of both the specified and measured total pressure levels in each individual screen area are compared. When the deviation of the measured average from the specified average total pressure is greater than the tolerance limit, that section is considered for modification.

The modification to each screen section may include a screen porosity change and/or a screen shape change. A change in screen porosity is accomplished in order to adjust the overall level of pressure downstream of a screen section. Individual screen shapes are changed to effect desired changes in pressure levels at discrete locations in the vicinity of screen junctions.

A test run is conducted with the modified screen configuration, and the measured total pressures are compared with the specified values. Modifications and their associated test runs are continued until the measured and specified total pressure values agree within the required limits.

SECTION IV
RESULTS AND DISCUSSION

A design technique was developed which would produce initial distortion screen specifications for any required pressure profile and, by utilizing test data from the initial screen configuration, would define the modifications to the initial screen configuration which would produce a specified point-by-point profile within a given tolerance.

This report presents a discussion of the design technique and example results from its application. Also described are the screen pattern fabrication procedures and the effects of the distortion screens on wall static pressures upstream of the screens. Measured total pressure loss data for screens of different porosities are presented. The total pressure distortion produced by a 180-deg solid plate is included.

4.1 A TECHNIQUE FOR DISTORTION SCREEN DESIGN

A technique was developed to produce a complex screen pattern which would give a specified total pressure profile at the simulated engine inlet. The method is based on the general requirement that the specified profile is to be reproduced on a point-by-point basis; that is, the desired pressure levels are defined at discrete locations in the flow annulus. The method is applicable for any number of locations. The profiles generated during this investigation were defined by using 48 measured values located on an equal area basis.

Since the basic objective is the point-by-point duplication of pressure values at Station 2, the procedure presumes that the measuring capability for each location is available. If the locations of the measured and desired values are not compatible, then the desired values may be extrapolated to the measuring probe locations. The extrapolation can be accomplished using profile maps generated with a mapping program as described in Appendix I.

The specified pressure profile was defined for the flow annulus at the simulated engine inlet plane, and the distortion screens were located upstream in a cylindrical duct. In this case, the desired pressure profile was transposed to the plane of the distortion screens using a method of geometric similarity that maintains the same flow area weighting for each total pressure value at both planes.

A basic specification for this design procedure is that each screen section be comprised of a single layer of uniform porosity screen. The use of screen overlays is specifically avoided since the pressure loss for multiple layers of screen is difficult to predict, due primarily to the complexity of the physical model which must be mathematically described and to the uncertainty associated with the installation of overlays. The use of single thickness, uniform mesh screens for each section provides a simple, repeatable physical model whose pressure loss characteristics can be accurately predicted.

The design technique is separated into two major application categories (Initial Screen Selection and Screen Modification) as described in the following sections.

4.1.1 Initial Screen Selection

The initial screen selection is accomplished by determination of the number and shape of the screen sections and the assignment of porosity levels to each section.

4.1.1.1 Screen Boundary Selection

The screen boundaries are defined by lines of constant pressure as determined from a profile map of the desired pressure values (Appendix I). This selection procedure provides a means of determining the minimum number of separate porosity screens which are required.

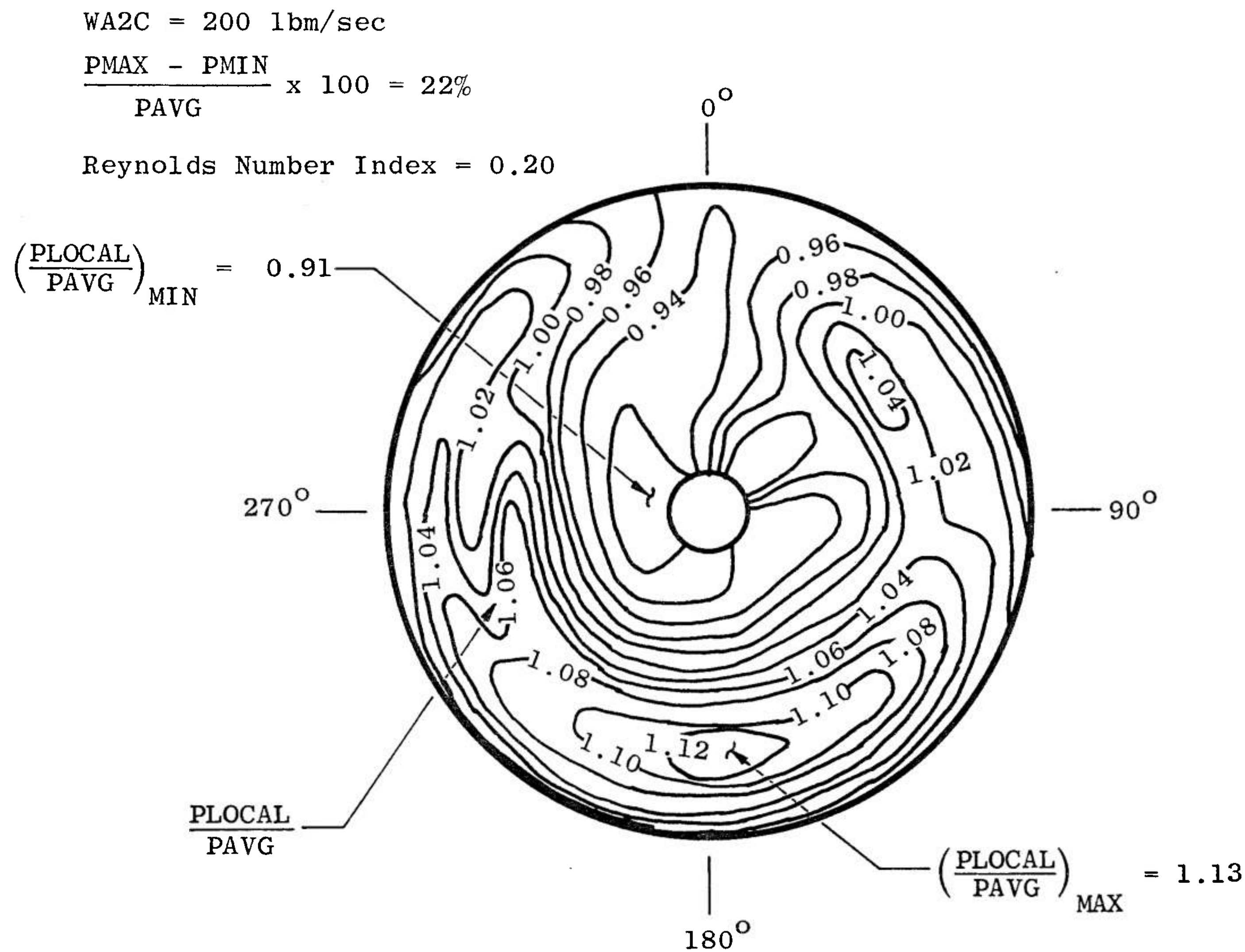
The desired total pressure profile map is generated for the plane of the distortion screen from the specified point-by-point pressure values. A sample pressure map is presented in Fig. 7a. When mapping the desired profile, the isobar interval is selected to be one-half the tolerance limit specified for the point-by-point reproduction; for example, an interval of 0.02 is selected for a tolerance limit of ± 2 percent. Only isobars plotted at this interval are considered for screen boundaries.

A separate porosity screen is assigned to each of the areas of specified pressure ranges in the profile map, and the isobars defining the limits of each specified pressure range are assigned as screen boundaries.

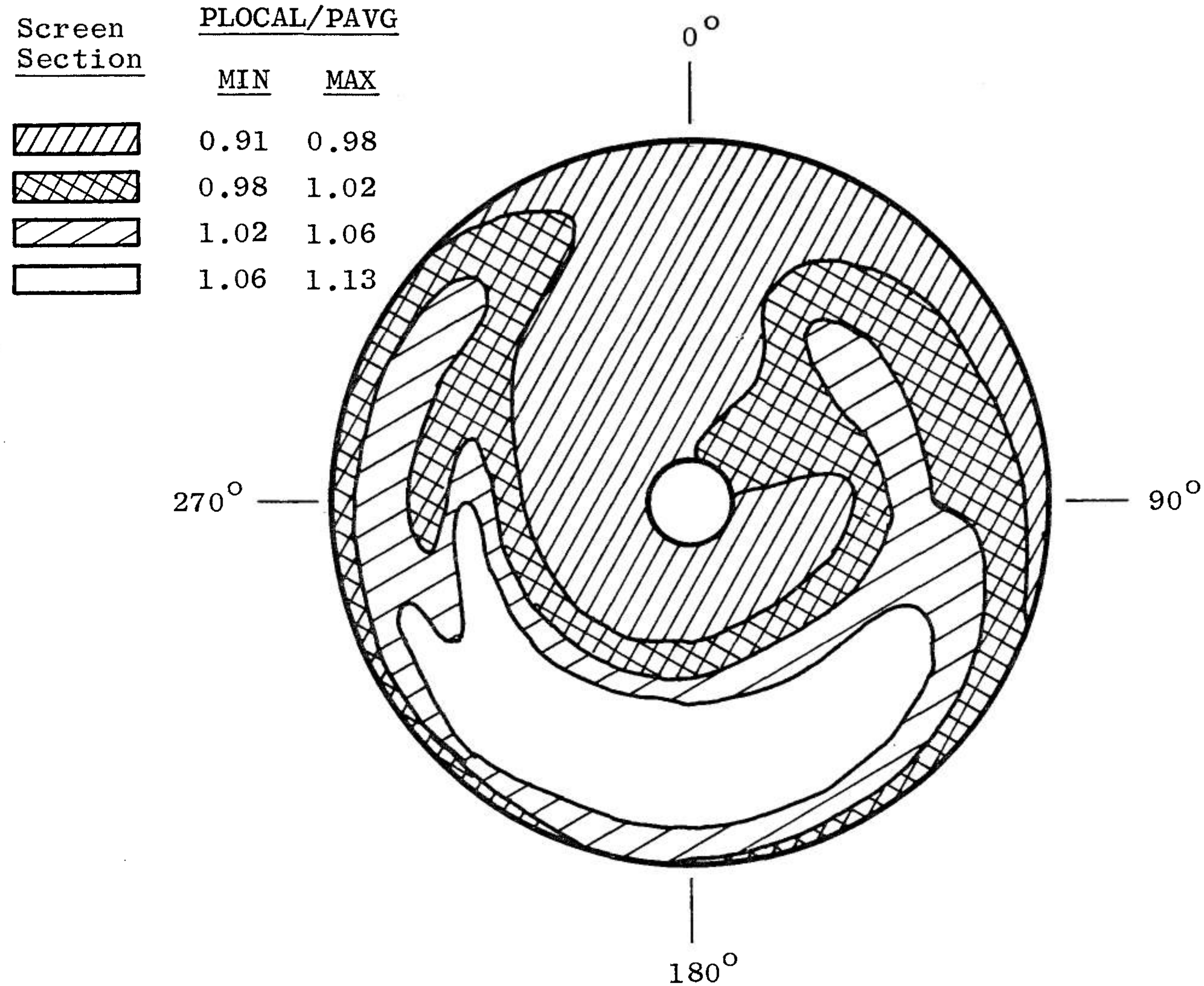
The pressure ranges are first defined for the highest and lowest porosity screens. Both screens must consist of an area that contains the extreme (highest or lowest) pressure value and a range of pressures as large as possible up to a maximum of twice the tolerance limit. For the sample profile with a tolerance limit of ± 2 percent (Fig. 7a), the highest porosity screen will include the highest pressure (PLOCAL/PAVG = 1.13) and may include a pressure range from 1.05 to 1.13 (ΔPLOCAL/PAVG = 0.08). Since the 1.05 isobar is not considered for a boundary in this case (because of the isobar interval criteria for screen boundaries), the 1.06 isobar is selected as the lower limit of the pressure range. The area bounded within the 1.06 isobar is, therefore, assigned as the highest porosity screen section (Fig. 7b).

The pressure range for the lowest porosity screen is determined in a similar manner. For the sample case (Fig. 7a), the minimum PLOCAL/PAVG is 0.91. Applying the ΔPLOCAL/PAVG = 0.08 criteria would allow the minimum porosity screen to cover the area of pressure in the range from 0.99 $\geqslant$ PLOCAL/PAVG $\geqslant$ 0.91. Again, because of the isobar interval criteria for screen boundary selection, the pressure range selected for this screen is from 0.91 to 0.98. The 0.98 isobar, therefore, defines the area of the lowest porosity screen.

The isobars selected as boundaries for the highest and lowest porosity screens are defined as characteristic isobars for the pressure pattern. The total pressure transition between the characteristic isobars is accomplished in pressure increments equal to the tolerance limit, and a separate screen section is assigned to each pressure increment. For the sample case with a tolerance limit of ± 2 percent, the transition from the 0.98 to



a. Desired Station 2 Total Pressure Profile at the Plane of the Distortion Screen
Fig. 7 Typical Initial Screen Boundary Selection Maps



b. Selected Screen Pattern for Initial Configuration
Fig. 7 Concluded

1.06 characteristic isobars is made in PLOCAL/PAVG increments of 0.04, and the remaining screen sections are assigned to the two areas with pressure ranges of 0.98 ≤ PLOCAL/PAVG ≤ 1.02 and 1.02 ≤ PLOCAL/PAVG ≤ 1.06.

The initial screen pattern selected for the sample profile is, therefore, comprised of four screen sections with the 0.98, 1.02, and 1.06 isobars and the duct wall and centerbody completely defining the screen boundaries as shown in Fig. 7b. From this scaled screen pattern, the area of each screen section is determined by planimeter measurements along the defined boundaries.

If the transition from the highest to lowest porosity screen cannot be accomplished in the selected increments with the characteristic isobars as previously defined, then one "new" characteristic isobar is selected from either the high or low pressure zone. This "new" isobar is selected adjacent to an initial characteristic isobar in the direction of the extreme value of that area. From a comparison of the possible "new" characteristic lines (high and low pressure zones), the selection is made as the one which will subtract the largest area from either the high or low pressure area. For example, if the initial selection of characteristic isobars for the sample profile (Fig. 7a) had been 0.98 and 1.04 (as would have been the case if the maximum PLOCAL/PAVG was 1.11), then the transition could not be made in even multiples of the tolerance limit (0.04). Therefore, the two isobars that may be selected as the "new" characteristics are the 0.96 or 1.06 constant pressure lines. The isobar selected is the one which will add the largest area to the transition zone. From planimeter measurements of the areas, the 0.96 isobar adds the most area and is defined as the "new" characteristic isobar.

4.1.1.2 Screen Porosity Determination

After the screen boundaries have been established, the porosity of each screen section is established by a determination of the ideal values and the best approximation of these ideal values which can be made with available screen stock. The ideal porosities are obtained from a theoretical calculation of the required flow area contraction for each screen which will give a pressure loss compatible with the desired downstream pressures. The basic assumptions utilized in these calculations are:

1. The porosity of the lightest screen is known. Normally this will be an unrestricted area (base grid only).

2. There is no mixing of the flows through screens of different porosity.

3. The total pressure at the plane of the screen is equal to the total pressure upstream of the screen.

4. The static pressure is uniform across the duct at the minimum area plane of the screens.

5. The static pressure immediately ~~downstreams~~ downstream of the screen is equal to the static pressure at the minimum area plane of the screen.

6. The total pressure immediatcly downstream of each screen is uniform across its area and equal to the arithmetic average of the specified total pressure values in that area.

The calculations are an iterative solution of the continuity equations at different flow stations. The specific equations are presented in Appendix I.

The screens are selected from available stock to conform as closely as possible to the ideal porosities. This is generally a sufficient specification to allow the initial selection; however, in the event that more than one combination of screens appear satisfactory, a calculation is made for each combination to determine the downstream pressure levels that will be produced. The calculated pressure levels for each screen are compared with the average of the desired values for each screen area, and the combination that produces the profile which best approximates the desired total pressure profile is selected as the optimum initial combination.

An additional variation of the procedure which may be employed to best match the available screens with the ideal porosities is the ability to select the absolute porosity range by varying the starting point (minimum restriction) for the ideal porosity calculation. If the available screen stock covers a narrow range of porosities, then the ideal porosities may be selected to include the highest porosity (most open area) screen from this group as the starting point. This is accomplished by including in the initial assumption (1) that the porosity of the lightest screen in the pattern is to be equal to the porosity of the lightest screen from the available group.

4.1.1.3 Sample Results

The results of applying the design technique for a typical desired total pressure profile are presented Fig. 8. The desired point-by-point profile is that previously used as an example for the initial screen boundary selection (Fig. 7a). The initial screen configuration produced measured total pressure values which deviated from the desired values in the range of ±10.5 percent for specific locations. The overall agreement as defined by the standard deviation (based on 48 locations) was 5.9 percent. For three similar specified point-by-point profiles, standard deviations for the initial screen selection of 1.2, 4.6, and 5.6 percent were obtained. With the initial screen selection for a profile nearly representing a 180-deg, one-per-revolution, step change profile, the standard deviation was 0.8 percent.

4.1.2 Screen Modification

The screen modification procedure provides a means of determining the changes which may be made to an existing screen configuration to improve the agreement between the actual and desired profiles. The modification procedure utilizes two basic methods of improving the screen design (Screen Porosity Modification and Screen Pattern Tailoring). These two methods are employed concurrently for each modification.

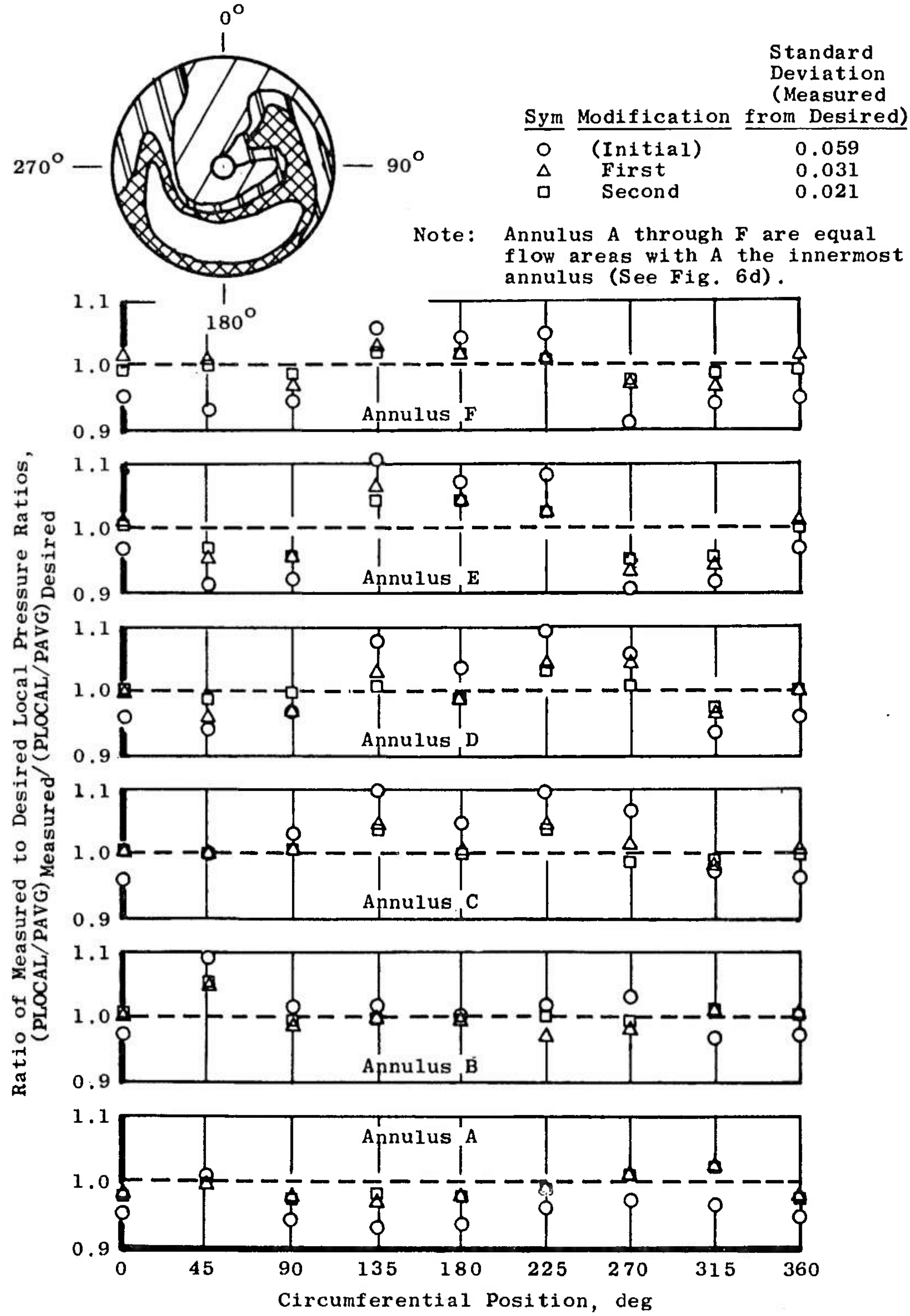


Fig. 8 Comparison of Station 2 Measured and Desired Total Pressure Profiles for a Typical Initial Screen Configuration and Subsequent Modifications

4.1.2.1 Screen Porosity Modification

The screen sections which require a change in screen porosity are determined by a comparison of the average measured pressure downstream of the section with the average of the desired pressures for that section. For this comparison, the average pressure is defined as the arithmetic average of all Station 2 probe measurements which lie within the boundary of a screen section after the profile has been projected to the plane of the screens. For each screen area which has an average pressure level out of the tolerance limit ($0.98 \leqslant$ PAVG measured/PAVG desired $\leqslant 1.02$ for the sample profile), a replacement screen for that area is considered. In each case, the available screen stock is audited, and possible substitutions are selected. It is recommended that proposed changes in any section porosity be limited to within ±10 percent of the original porosity for each iteration.

From the screen changes that are selected, the several possible screen combinations are determined. These combinations are then mathematically evaluated to predict the pressure profiles that will be produced. The predicted average pressures for each screen combination are compared with the desired average pressures, and the combination which most nearly approximates the desired values is selected as the new screen configuration.

The basic assumptions used for these calculations are the same as those for the Initial Screen selection, with the following exceptions:

1. The total pressure loss coefficient for each screen section is determined from measured data taken during the initial configuration test.

2. The predicted total pressure loss coefficient for a "new" screen is proportional to the loss coefficient for the "old" screen times the ratio of the screen open areas.

3. The porosities of all screen sections are known.

The pressure loss coefficients determined from measured data account for the mixing and attenuation of the total pattern profile that occurs in the distance from the screen plane to the pressure measuring station. Since the pressure loss coefficients are determined from measured data, this calculation method automatically compensates for the distance between the screen plane and the pressure measuring station.

4.1.2.2 Screen Pattern Tailoring

A significant part of the modification procedure is the pattern tailoring or screen boundary adjustments which are required to effect changes in pressure levels in screen interface areas. Screen tailoring is accomplished for two basic situations: (1) to locate the junction of two screens relative to a measuring probe such that the pressure level at that probe will be at a specified level between the average pressures behind the two screen sections, and (2) to locate a screen section relative to a measuring probe such that the pressure level at the probe will be equal to the average pressure downstream of that screen section. In both cases, it is necessary to know the basic transition

characteristics of pressure rate of change and transition zone boundaries. The preferred method of determining these characteristics is from a measured pressure profile. However, in most cases the number of measurements will not be adequate to define these characteristics, and therefore, an estimate must be made.

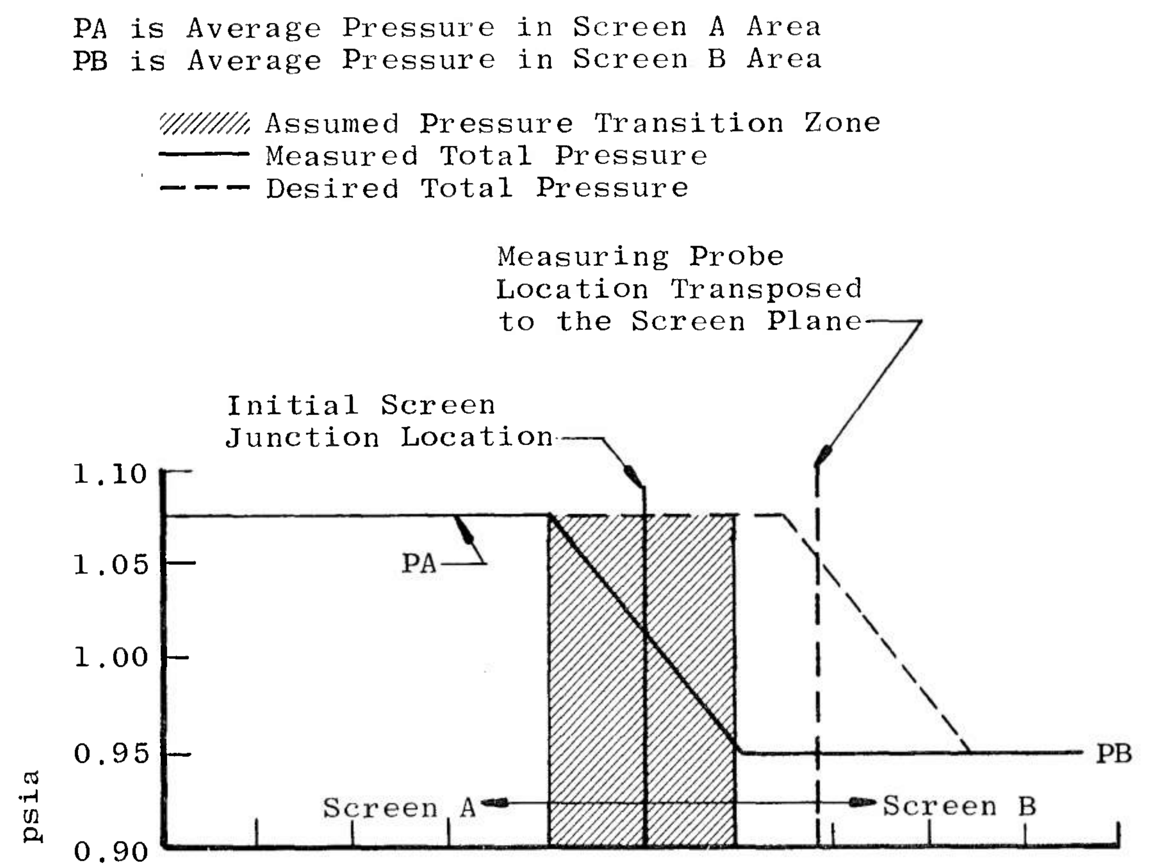
The transition zone boundaries are established first. The measuring probe locations are projected to the plane of the distortion screens, and the pressure measurements from probes located near the screen junction are evaluated for an indication of the transition zone width in this plane. Each transition zone width is a function of both the difference in average pressure level on each side of the transition zone and the axial distance from the screen plane to the pressure measuring station. If data for a specific configuration are not available to define the transition, projected to the plane of the screens, the transition width is assumed to occur within a distance of ±1 in. from the junction of the two screens. If measurements which define the transition rate are not available, then the pressure rate of change is assumed to be constant across the transition zone.

An example illustration for effecting a desired change by relocating the transition zone is presented in Fig. 9. For this case, the measured pressure at a discrete location is lower than the desired value, and the desired value is between the average levels for the two screens. It is necessary then to relocate the screen junction to effect a desired pressure increase at the measurement location. The transition zone width is assumed to be ±1 in. from the junction of the two screens, and the total pressure transition rate through the zone is constant. From the measured data, the total pressure transition profile through the transition zone is constructed (Fig. 9). The transition profile is then shifted relative to the pressure measuring location such that it describes the desired pressure level at the measuring probe location (Fig. 9). The screen junction is then moved as required to maintain the same relative position with the pressure profile.

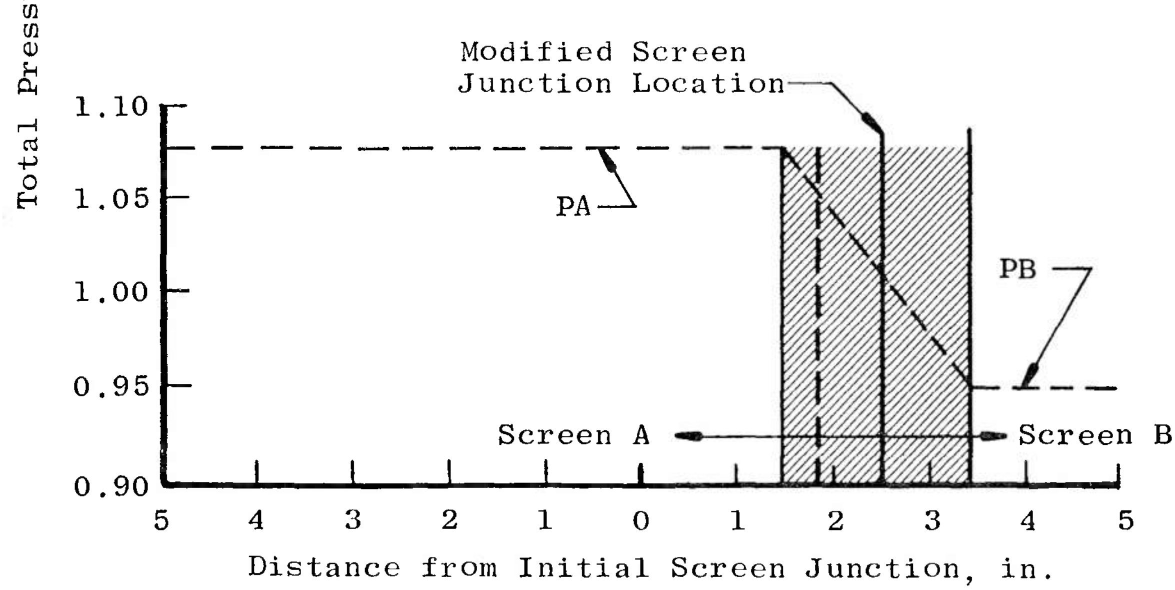
This procedure locates a single point for the modified junction location of the two screens, and the patterns are altered to place the screen junction through the selected point. The screen boundary alterations are accomplished in a smooth transition in order to minimize the effect on the overall pattern (no abrupt contour changes are added to the screen pattern).

4.1.2.3 Sample Results

The results of applying the modification technique to reduce the deviation of measured from desired values are also graphically presented in Fig. 8 for the previously selected set of desired values. The first modification to the initial configuration reduced the overall deviation (one standard deviation) from 5.9 to 3.1 percent, and the second modification effected a further reduction to 2.1 percent. At the end of two modifications, the maximum difference (measured and desired values) for individual locations was reduced from ±10.5 percent for the initial configuration to ±5.5 percent. In order to reduce the maximum difference for all locations to the ±2 percent tolerance limit, additional modifications would be required.



a. Initial Screen Junction Total Pressure Profile



b. Modified Screen Junction Total Pressure Profile

Fig. 9 Total Pressure Profile for Initial and Modified Screen Junction Locations

The point-by-point agreement that may be expected from applying the initial screen selection and screen modification techniques for complex screen patterns is graphically presented in Fig. 10. The curve is based on experience with five complex screen patterns which had distortion levels on the order of a (P2MAX-P2MIN)/P2AVG of approximately 0.20. The point-by point agreement of measured and desired total pressure that may be expected from the initial screen is about 5.0 percent and should decrease to about 2.0 percent by configuration No. 4 (third modification).

4.2 STATION 2 TOTAL PRESSURE REPEATABILITY

The repeatability of the steady-state total pressure profile produced by each screen was established by recording data behind each screen during five separate data points. Screen approach Mach number and pressure level were perturbed between each data point and then reset within the limits of plant repeatability. The repeatability of the standard deviation $[(\sigma - \sigma AVG)/\sigma AVG]$ is presented as a function of normalized airflow (Fig. 11). For any given airflow rate, the repeatability of the standard deviation for any screen is about ± 0.75 percent.

4.3 SCREEN FABRICATION TECHNIQUE

Fabrication of each screen section in the composite pattern is accomplished from a full-scale template of the pattern. The template is generated by photographically enlarging the pressure profile maps which are used to define the screen boundaries (Fig. 7). The full-scale pattern is bonded to a ply board backing, and the separate section patterns are cut from this composite using a band saw. A sheet of selected screen stock is stapled to the ply board template, and the screen is cut to the pattern shape. A band saw was also found to be the most effective means of cutting the screens. With the screen still attached to the template (to prevent skewing of the grid), the outer periphery of the section is welded to provide a rigid outer boundary. For screens of low porosity, a continuous weld is formed around the edge; for high porosity screens, the weld joint is made at the outermost junctions of the wire strands. During the process of screen development, the individual screens are safety wired to a backing grid which covers the entire duct area. This grid should be of as high porosity as possible (consistent with the structural requirements) in order to minimize the effects on the pressure loss characteristics of each screen. The individual screen sections that comprise the final configuration are weld joined to form a single unit.

4.4 EFFECTS OF DISTORTION SCREENS ON UPSTREAM STATIC PRESSURE PROFILES

The influence of distortion screens on inlet duct wall static pressure measured upstream of the screen plane is presented in Fig. 12 for five complex screen configurations and a 180-deg solid plate. For the five screen configurations, the variations are similar, with the variations approaching zero at 35 in. upstream of the screen plane. At a distance of 17.4 in. upstream of the distortion screen, the static pressure variation for a constant corrected airflow of approximately 150 lbm/sec ranged from 0.45 to 1.15 percent for the five screen configurations. The variation range was 0.95 to 2.30 percent at a distance of 8.7 in. upstream of the screen plane.

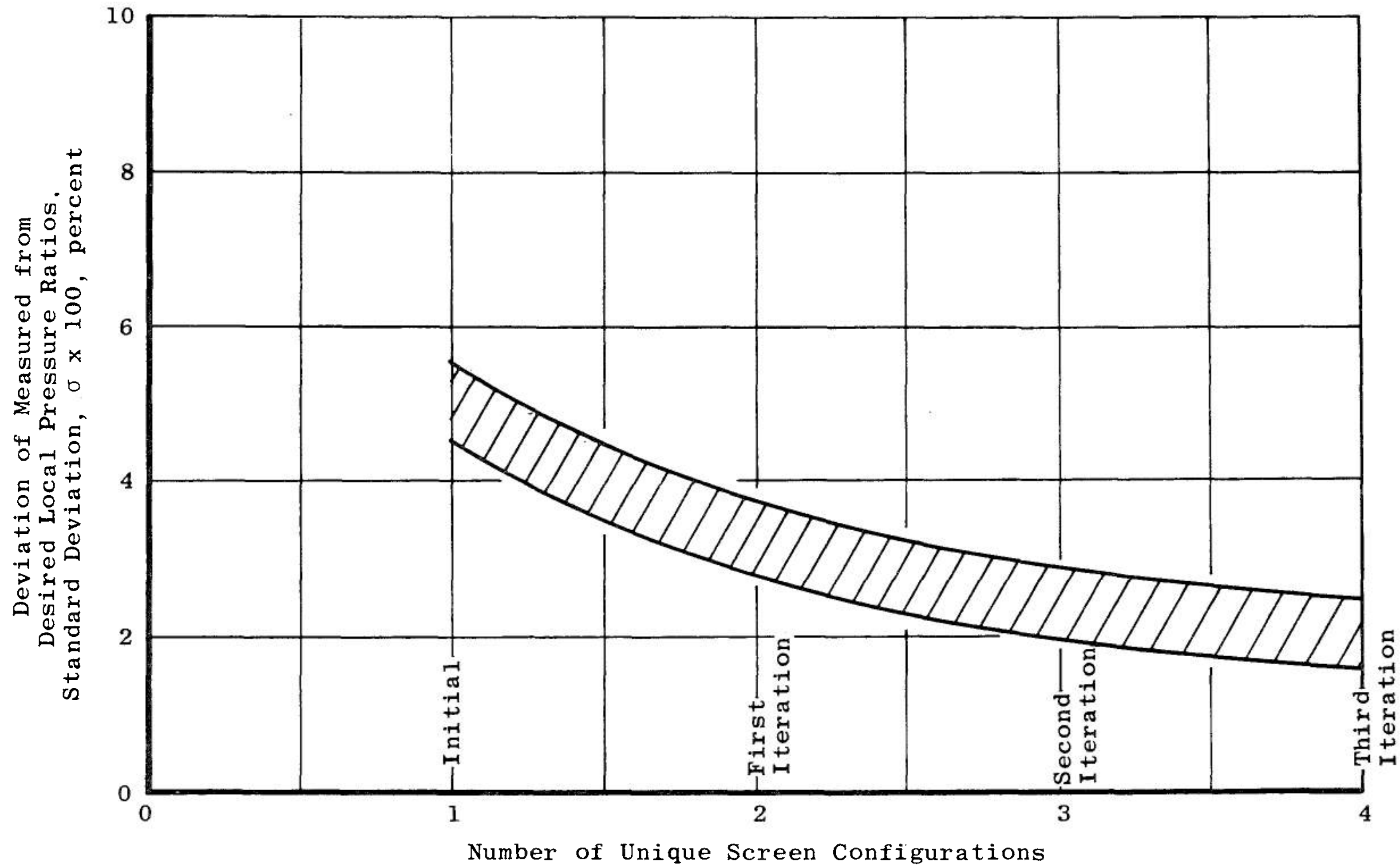


Fig. 10 Expected Reproduction of Desired Total Pressure Profile with Initial Screen Selection and Screen Modification Techniques

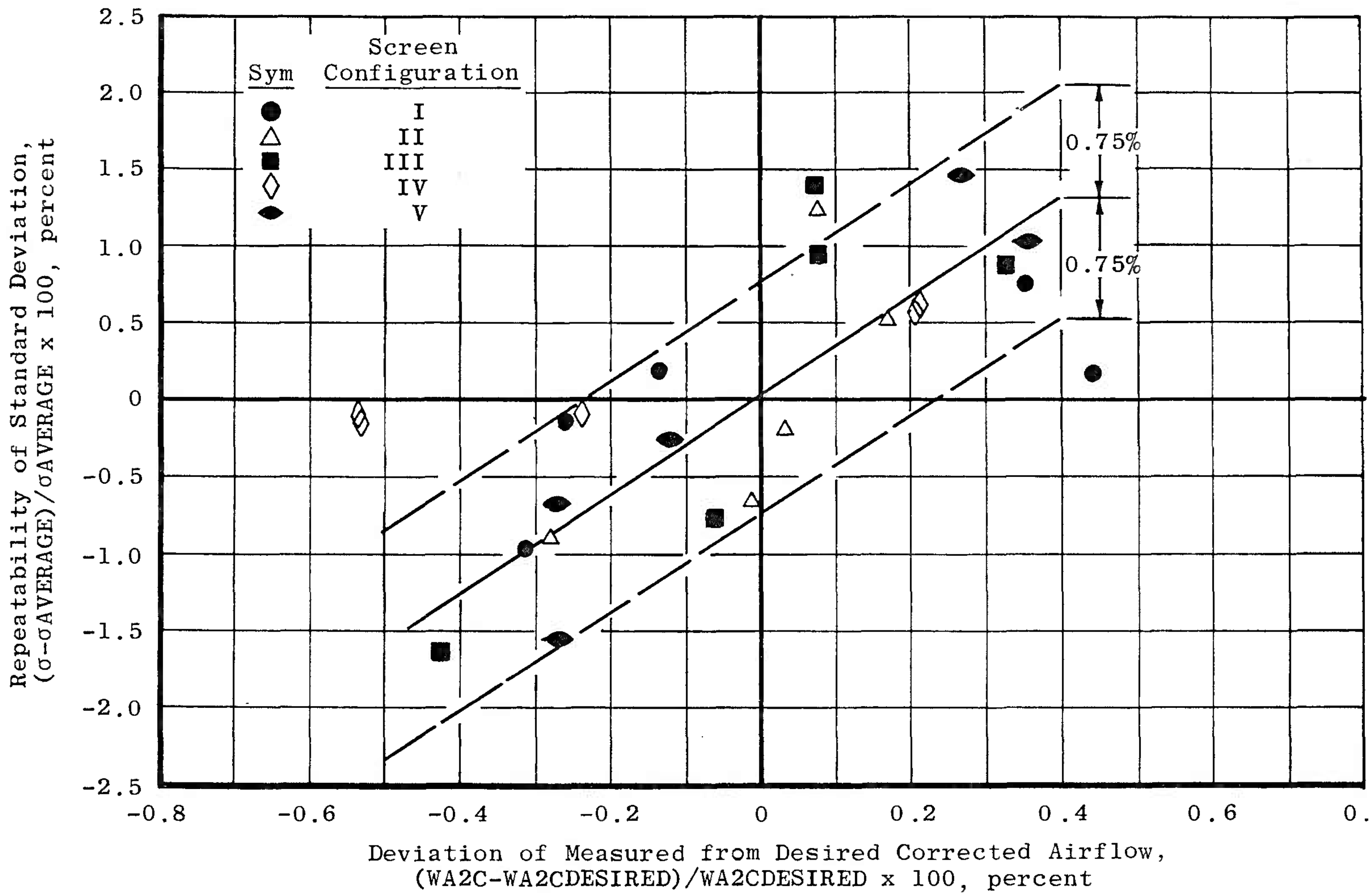
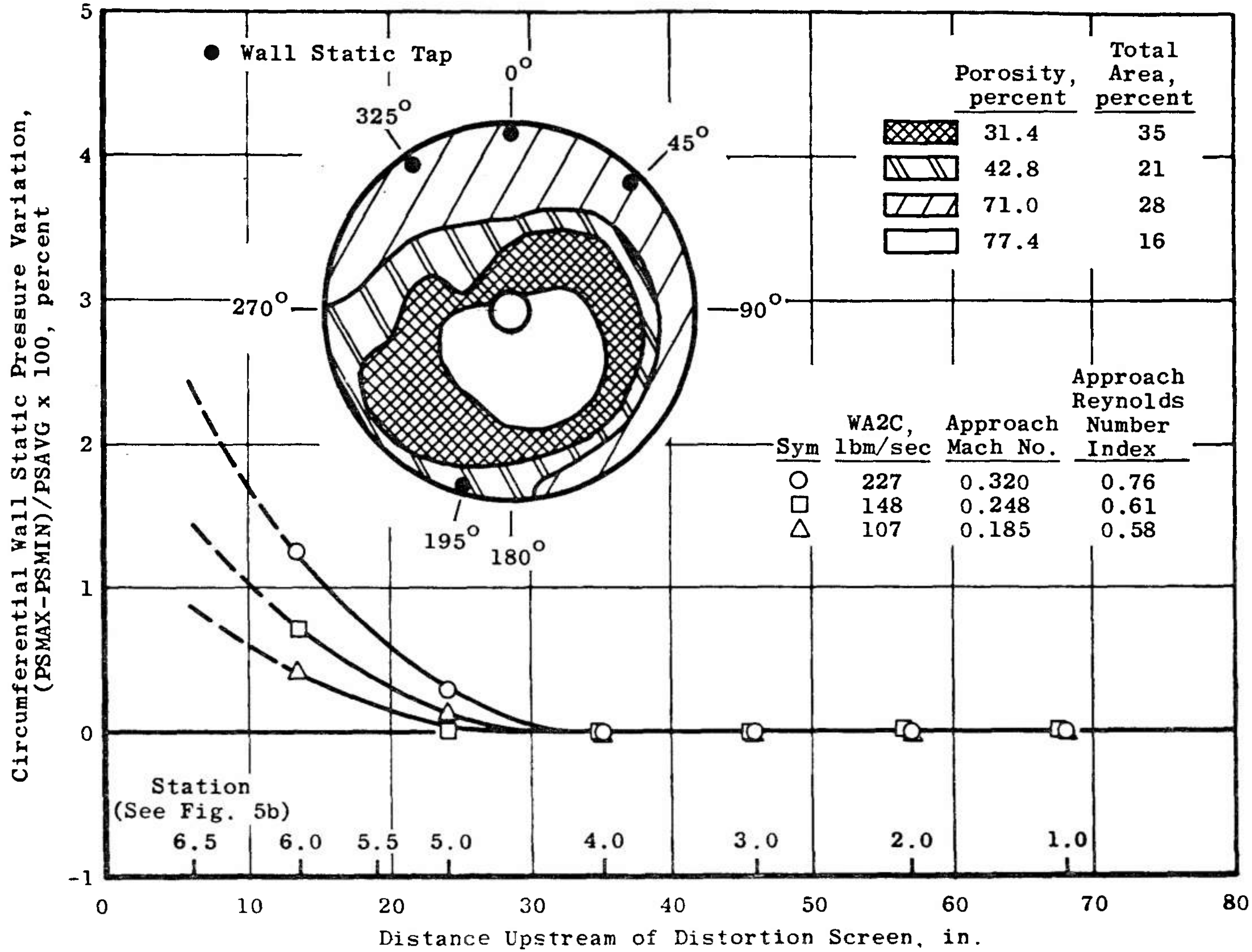
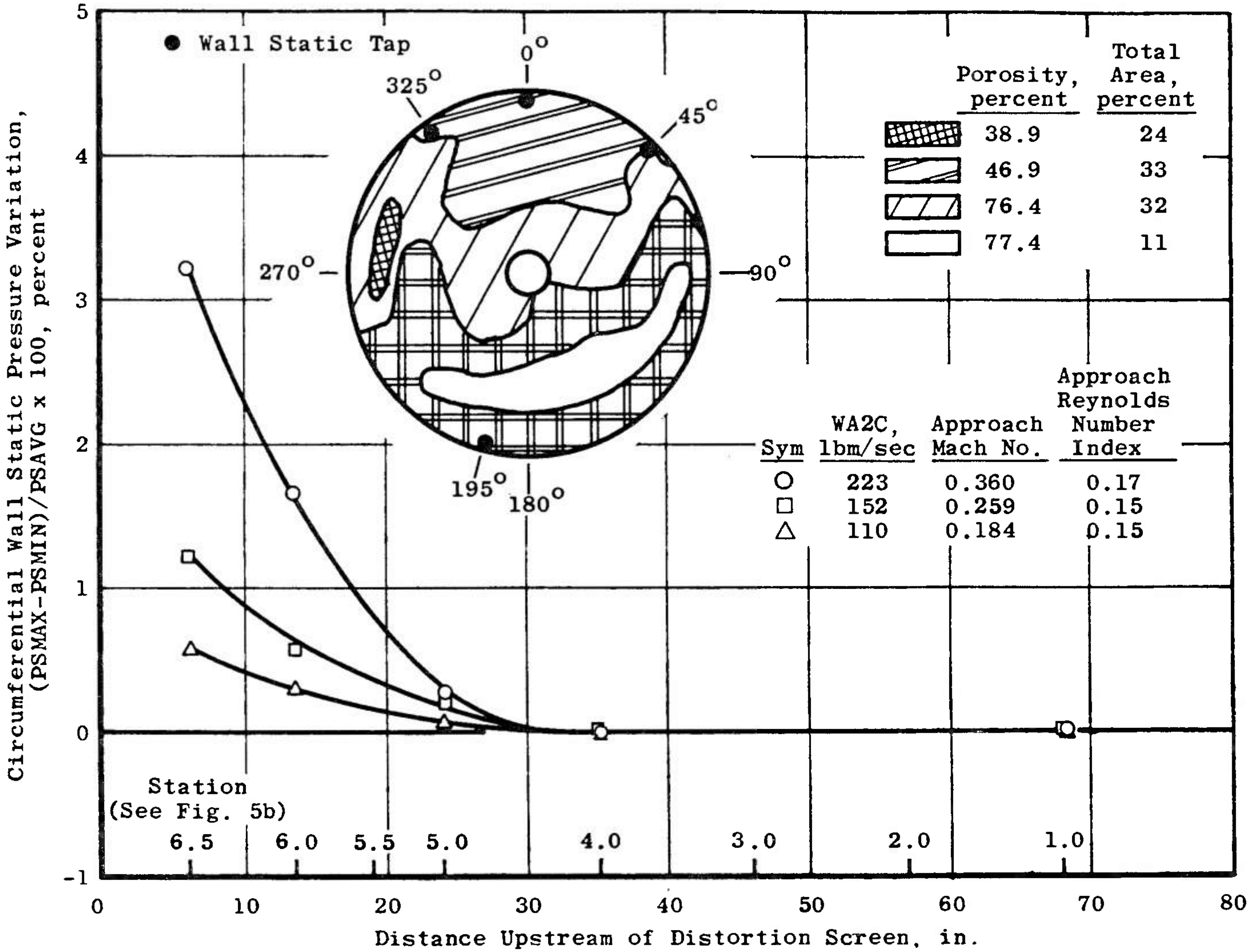


Fig. 11 Station 2 Total Pressure Profile Repeatability for Five Complex Screen Patterns

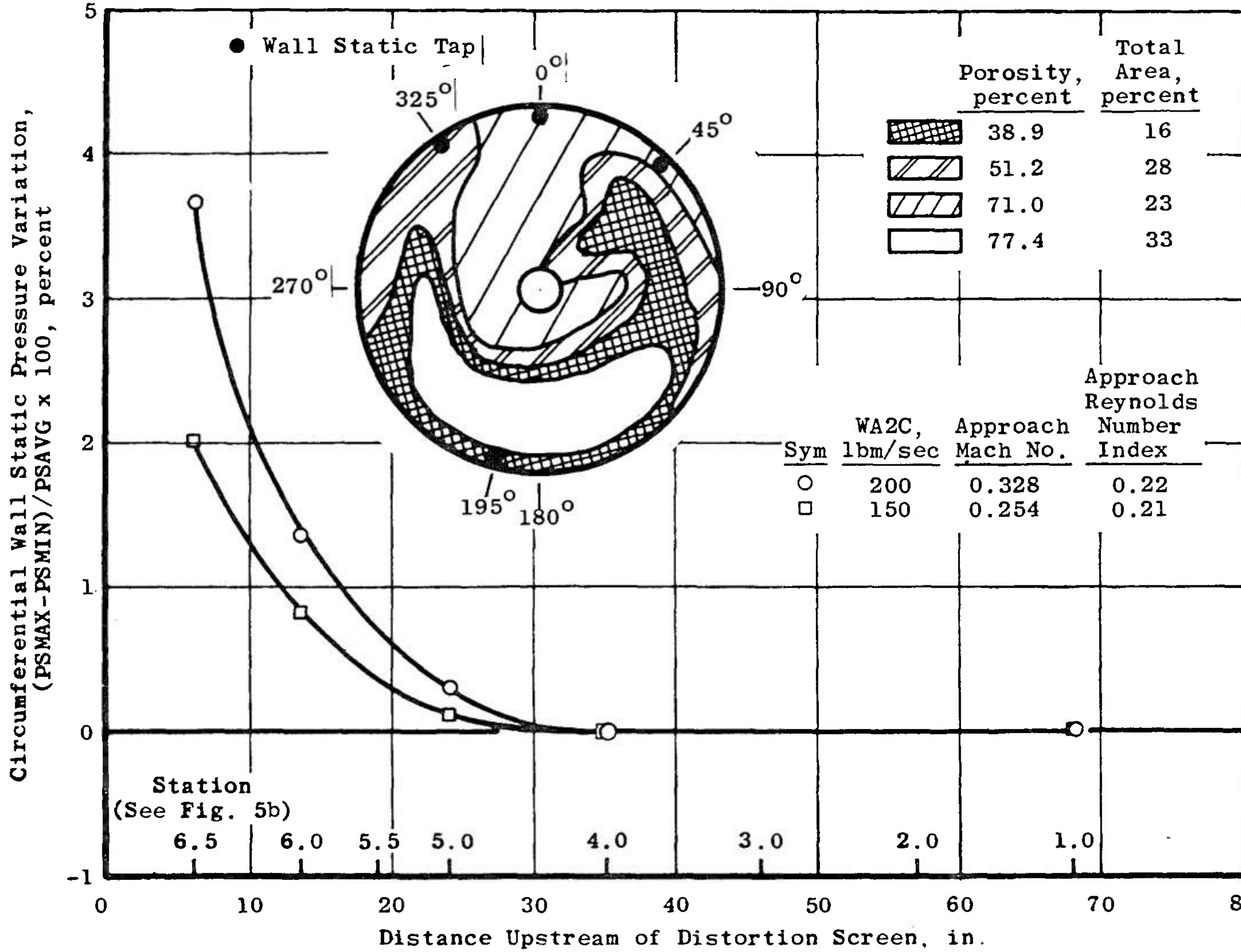


a. Screen Configuration I

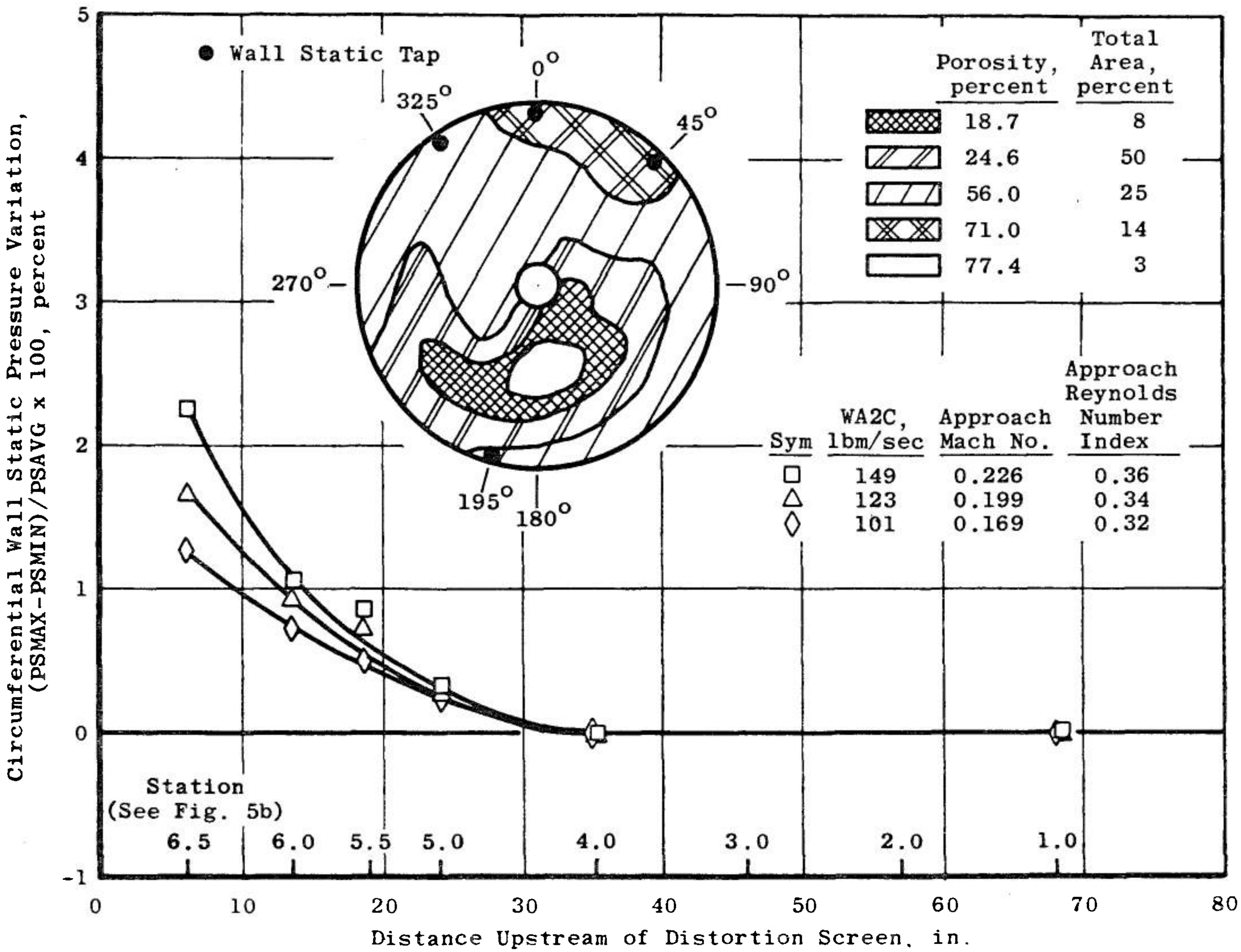
Fig. 12 Wall Static Pressure Variations Upstream of Distortion Screen Plane



b. Screen Configuration II
Fig. 12 Continued

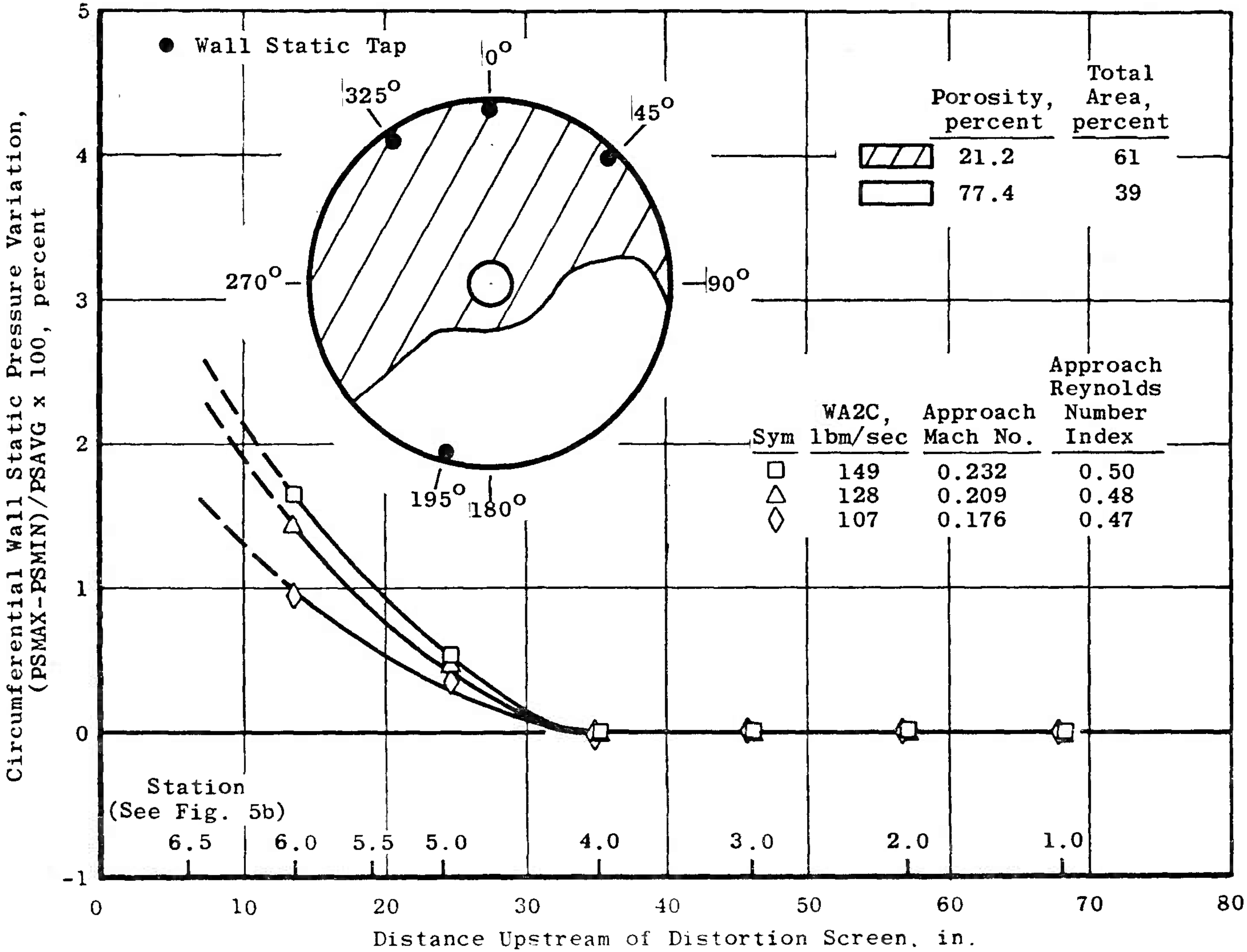


c. Screen Configuration III
Fig. 12 Continued

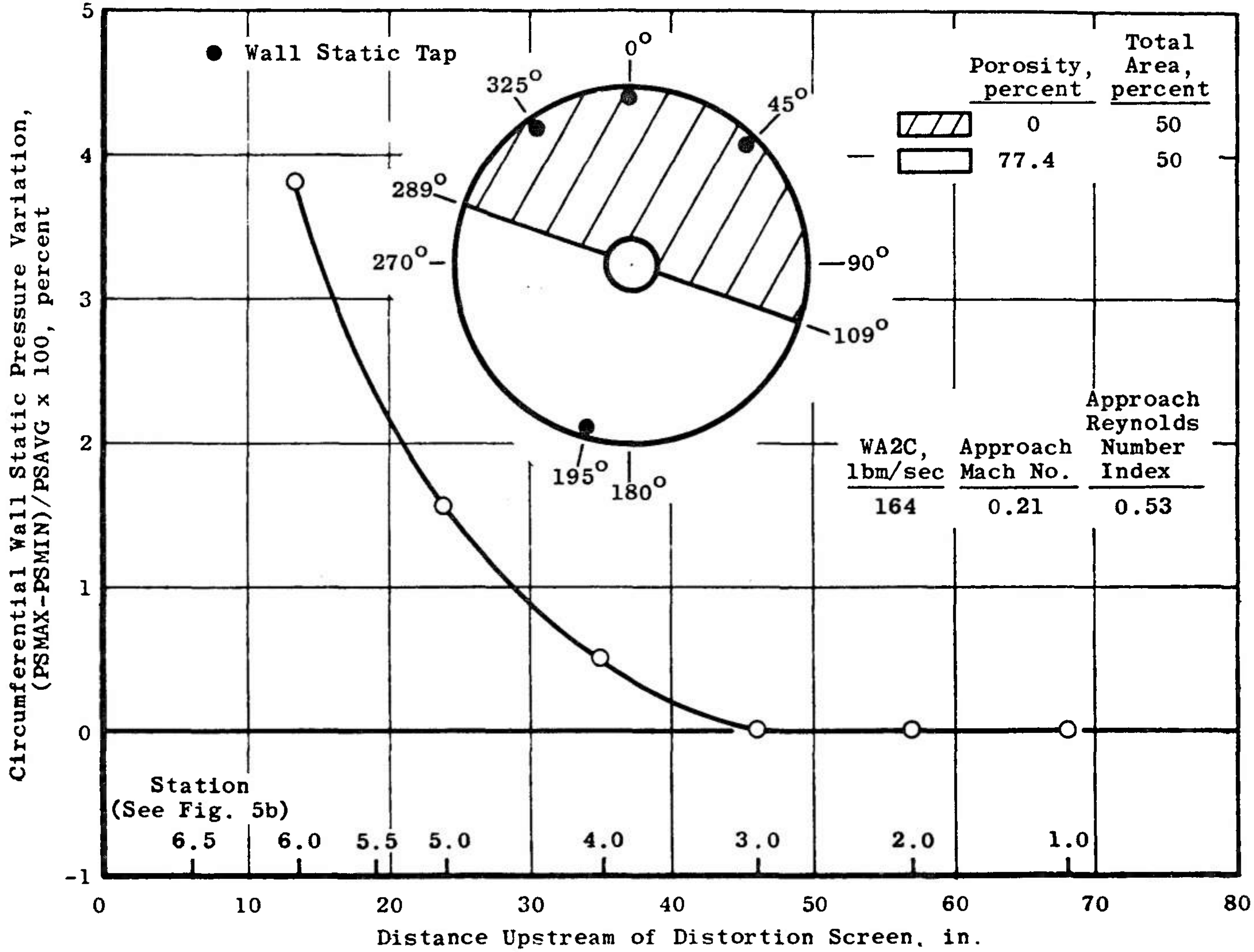


d. Screen Configuration IV

Fig. 12 Continued



e. Screen Configuration V
Fig. 12 Continued



f. 180-deg Solid Plate
Fig. 12 Concluded

A generalized static pressure function (PSFN) was developed from the data for the five complex distortion screens to provide a means of estimating the static pressure variations caused by any screen configuration. The generalized function includes factors that account for the influence of duct Mach number, gas density, total screen blockage, and the severity of the pattern on the static pressure variation upstream of the screen. The equation for the generalized static pressure function (PSFN) is included in Appendix I. The generalized static pressure function relative to the axial distance upstream of the distortion screen is presented in Fig. 13. The function continuously decreases from a maximum at the screen plane to zero at approximately 35 in. upstream of the screen.

An indication of the maximum static pressure variation that can be expected was obtained with the 180-deg solid plate (Fig. 12f), where the static pressure variation is propagated approximately 46 in. upstream of the plate. At 34.8 and 17.0 in. upstream of the plate, the variation was 0.5 and 2.8 percent, respectively.

4.5 MEASURED TOTAL PRESSURE LOSS

Screen pressure loss data are graphically presented in Fig. 14. The pressure loss was determined from the average of the pressure measurements from all probes located behind a screen section. Pressure loss data were obtained for the backing grid (1 in. center-to-center mesh of 0.125-in.-diam wire) and uniform mesh woven wire screens with porosity ranges from 18.7 to 76.4 percent. In all cases, the screens were installed over the backing grid, and the data include the effects imposed by the backing grid.

The measured total pressure loss exhibits consistent trends of increasing pressure loss with increasing airflow rate and decreasing screen porosity. The pressure loss was determined over a range of Reynolds number indices from approximately 0.1 to 0.5. The data are presented for reference and may be used for preliminary estimates for a similar installation.

4.6 180-DEG, SOLID-PLATE TOTAL PRESSURE DISTORTION

A secondary objective of the program was to determine the simulated engine inlet total pressure distortion produced by a 180-deg solid plate located 25 in. upstream of the inlet instrumentation plane. The total pressure distortion as a function of airflow is presented in Fig. 15a. The distortion level continuously increased with increasing airflow, ranging from 23.6 percent at an airflow of 110 lbm/sec to 53.4 percent at 164 lbm/sec.

The simulated engine inlet total pressure profile produced by the 180-deg solid plate is presented in Fig. 15b. The maximum pressure distortion [(PMAX-PMIN)/PAVG] was 0.534 at the maximum simulated engine inlet corrected airflow of 164 lbm/sec. The transition from the maximum to minimum pressure level ($1.30 \geqslant$ PLOCAL/PAVG $\geqslant 0.77$) as defined by the profile map of measured total pressure values occurred over a circumferential distance of approximately 40 deg.

$$PSFN = \left[\frac{\left(\frac{PSMAX-PSMIN}{PSAVG}\right)_d}{\frac{ql}{psl}}\right]\left[\frac{SMIN}{SMAX}\right]\left[\frac{1}{AT}\sum_{i=1}^{N}(Si)(Ai)\right]$$

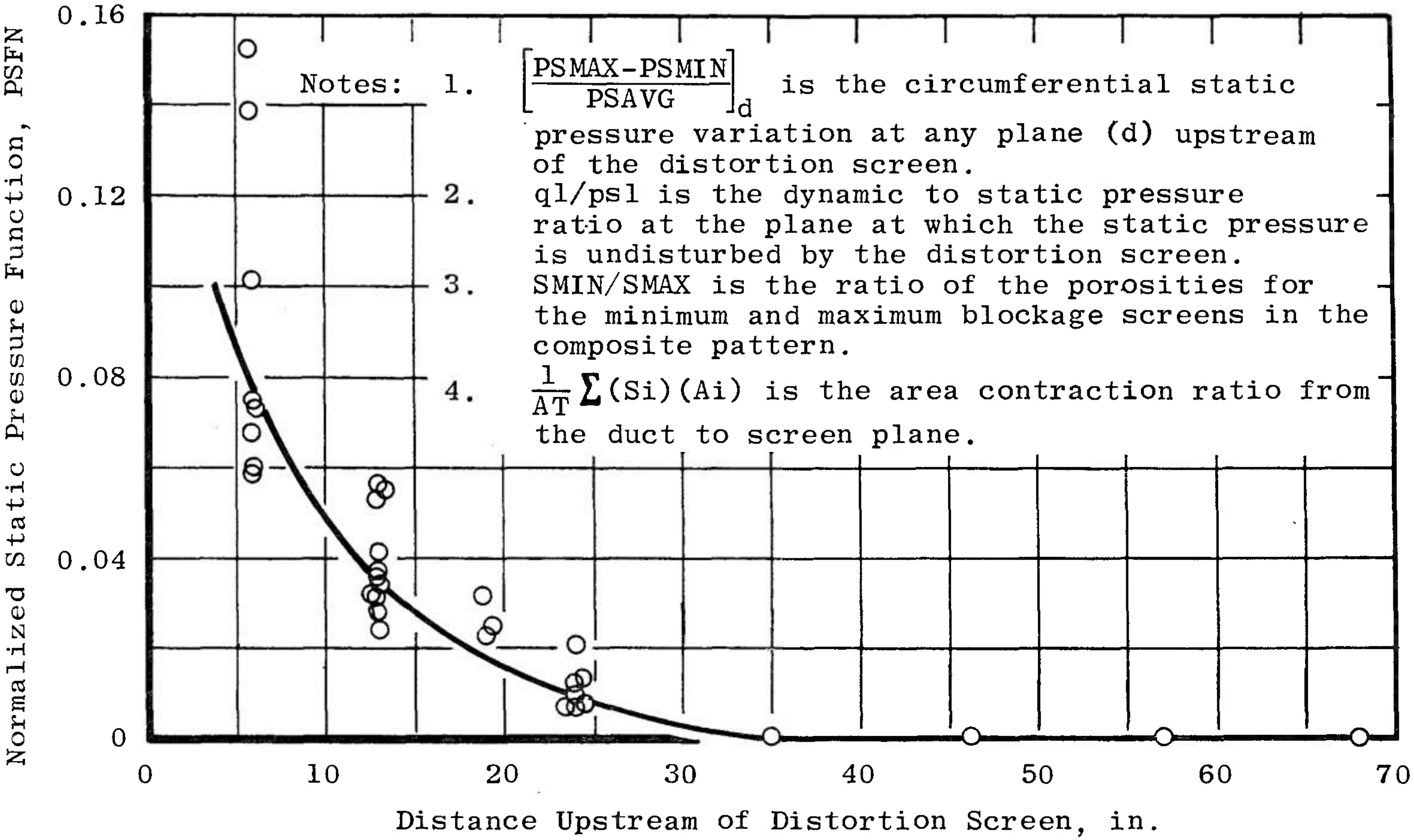


Fig. 13 Generalized Static Pressure Function for Complex Screen Configurations

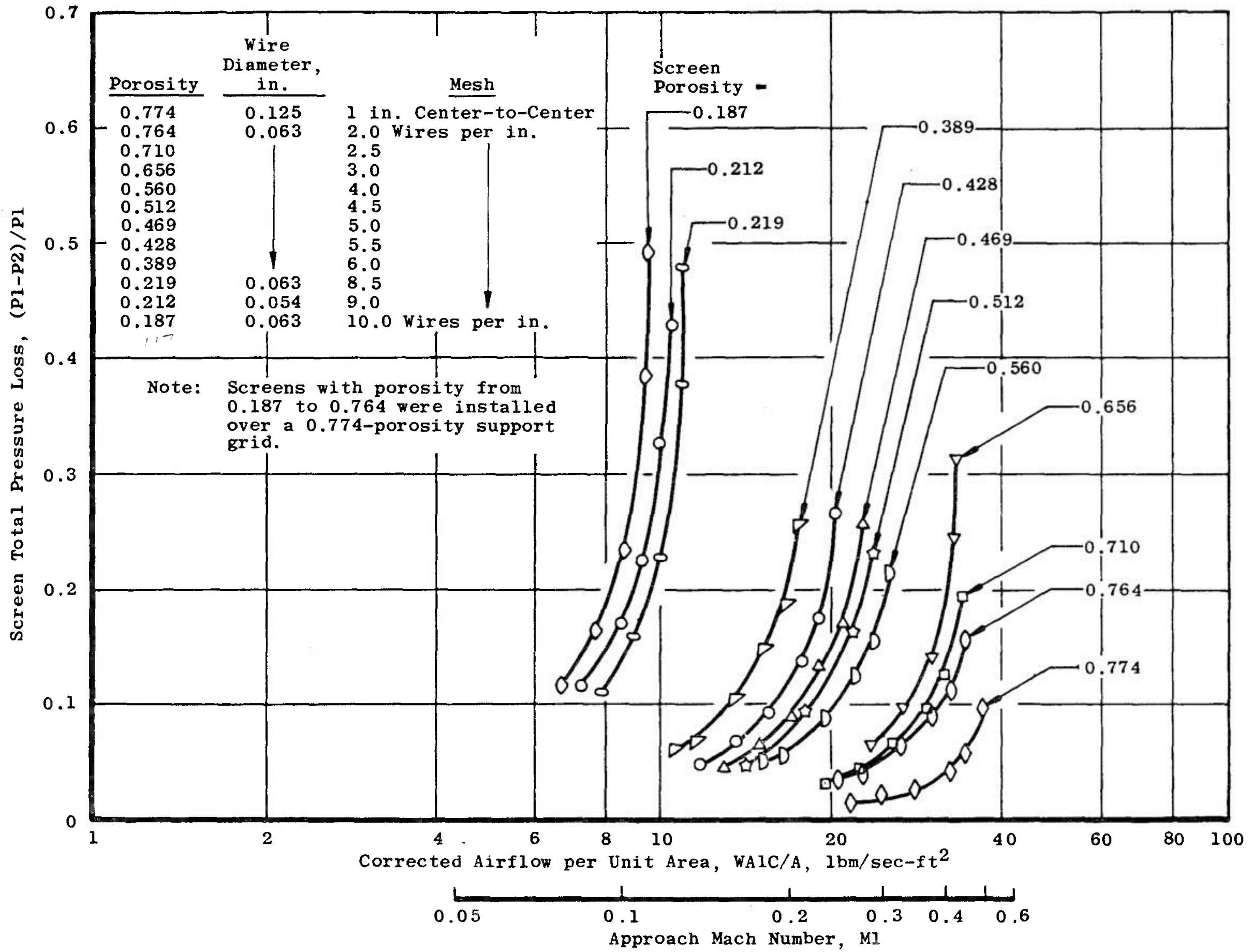
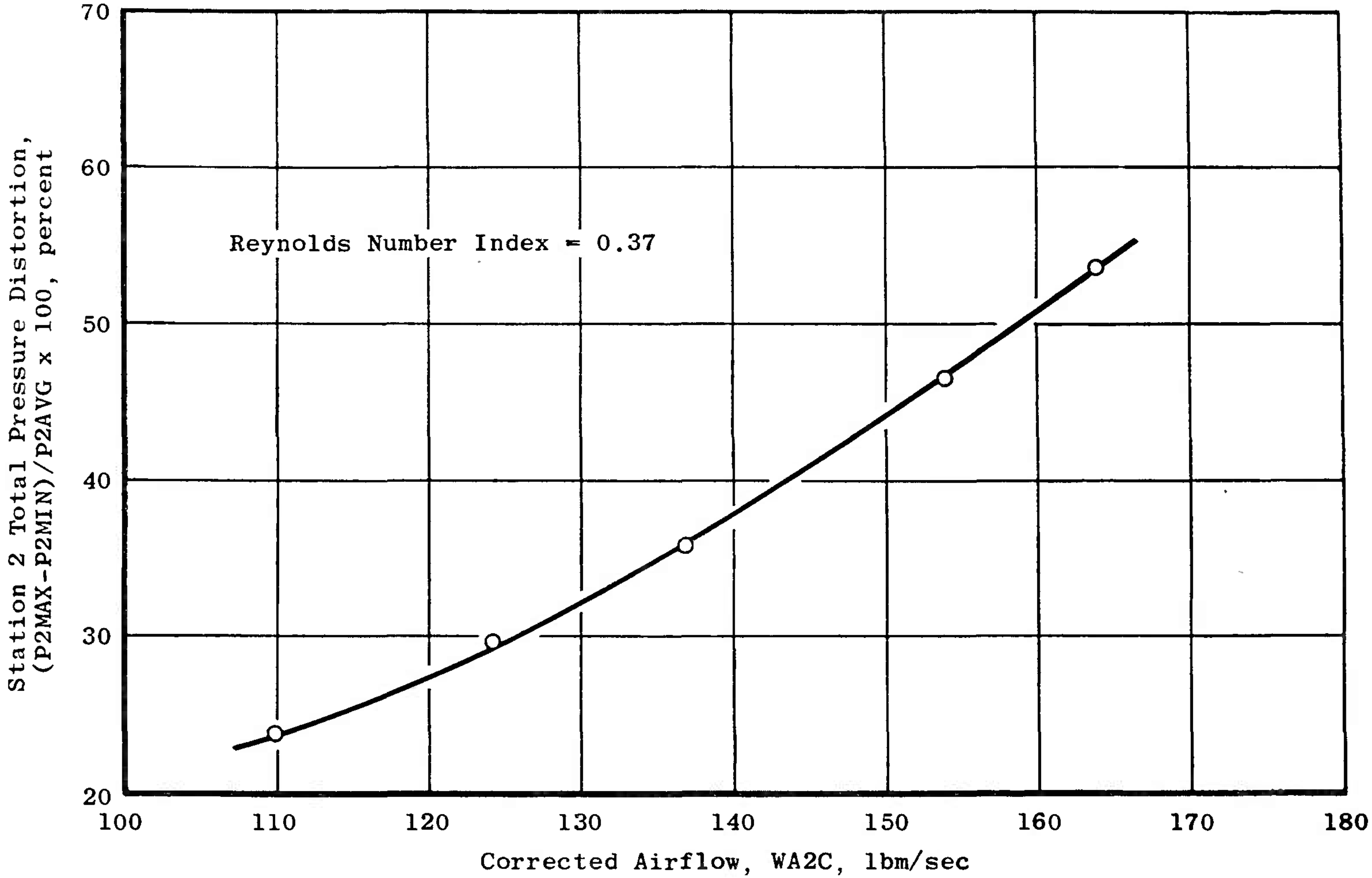
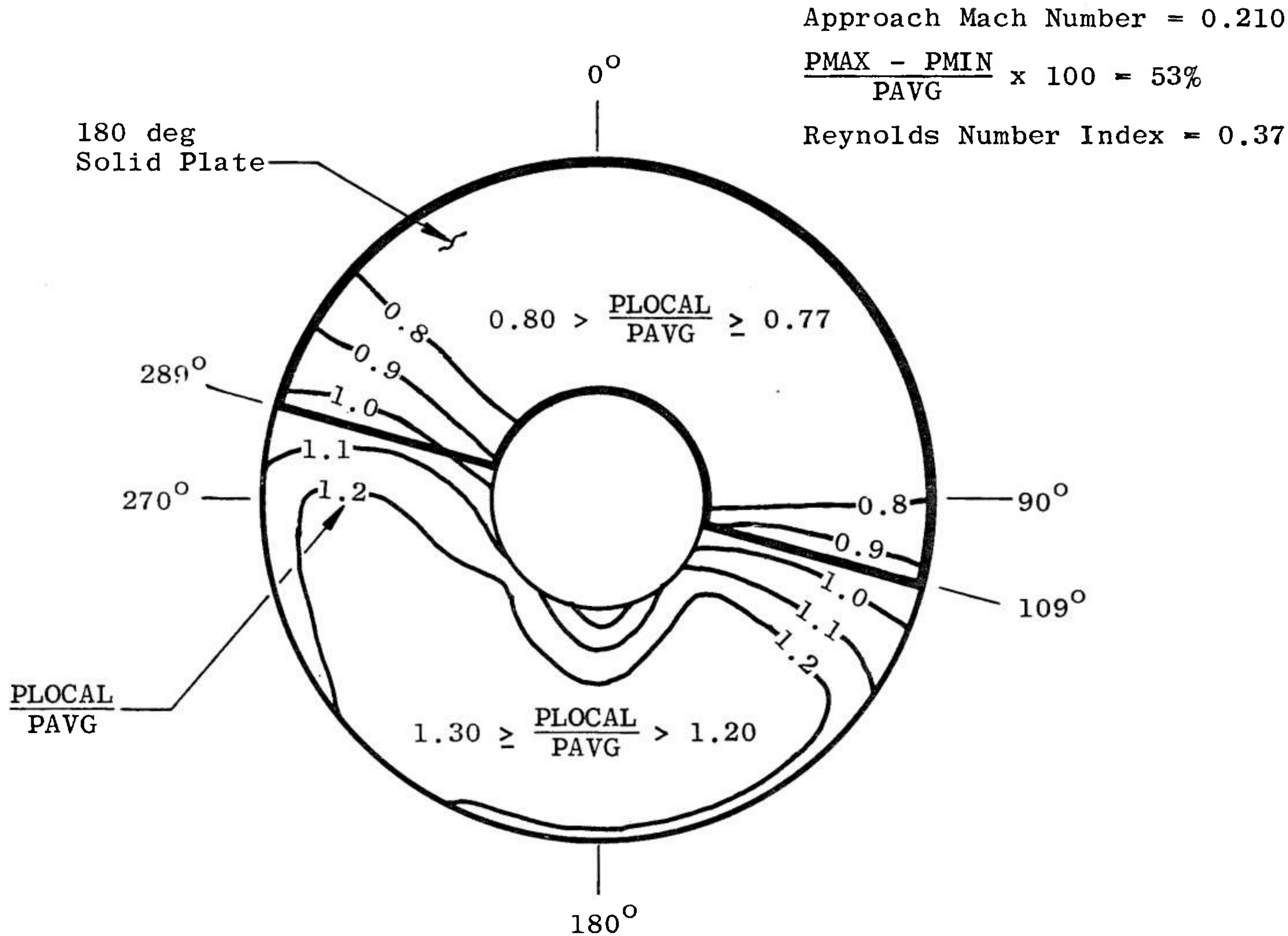


Fig. 14 Measured Total Pressure Loss for Uniform Mesh Screen Cloth



a. Total Pressure Distortion as a Function of Airflow
Fig. 15 Total Pressure Distortion Produced by a 180-deg, Solid Plate Located 25 in. (0.71 Duct Diameters) Upstream of the Measurement Plane



b. Total Pressure Profile at Maximum Airflow
Fig. 15 Concluded

SECTION V
SUMMARY OF RESULTS

The results of an analytical and experimental program to establish design techniques for the selection and installation of distortion screens to produce a specified total pressure profile at the inlet of a turbine engine may be summarized as follows:

1. The use of the Initial Screen Selection technique can be expected to produce an agreement between the measured and desired total pressure profiles based on a point-by-point comparison (48 discrete values at unique locations in the flow annulus) within a one standard deviation of 0.05.

2. The combined Initial Screen Selection and Screen Modification techniques can be expected to produce a screen pattern that will produce a screen pattern that will reproduce a desired total pressure profile on a point-by-point comparison of 48 locations within a one standard deviation of 0.025 with the initial screen and two modifications.

3. The repeatability of the total pressure profile produced by a complex screen, as defined by the standard deviation for the 48-point matrix, is ±0.75 percent at a specified airflow.

4. For a constant corrected airflow of approximately 150 lbm/sec, the wall static pressure variations upstream of the distortion screens were 2.3 and 1.2 percent of the average pressure at axial distances of 8.7 and 17.4 in. from the screen. The static pressure variation approached zero at 34.8 in. upstream of the screens. A normalized static pressure function was developed that provides a means of estimating the static pressure variation caused by any complex screen configuration.

5. The maximum total pressure distortion [(PMAX-PMIN)/PAVG] produced at a plane 24.8 in. downstream of the 180-deg solid plate was 53.4 percent at an approach Mach number (60 in. upstream of the plate) of 0.210.

REFERENCES

1. Test Facilities Handbook (Ninth Edition). "Engine Test Facility, Vol. 2." Arnold Engineering Development Center, July 1971.

2. Owens, C. L. "Calibration Capabilities of the ESF Instrument Branch." AEDC-TR-67-18 (AD648707), March 1967.

3. Smith, Robert E., Jr. and Matz, Roy J. "Verification of a Theoretical Method of Determining Discharge Coefficients for Venturis Operating at Critical Flow Conditions." AEDC-TR-61-8 (AD263714), September 1961.

APPENDIX I
METHODS OF CALCULATION

APPENDIX I
METHODS OF CALCULATION

General methods and equations employed to compute the steady-state parameters presented are given below. Where applicable, arithmetic averages of the pressures and indicated temperatures were used.

SPECIFIC HEATS

The specific heat at constant pressure was computed from the empirical equation:

$$CP = a_1 + b_1 T + C_1 T^2 \quad , \quad \text{Btu/lbm-°R} \tag{I-1}$$

where a_1, b_1, and c_1 are constants based on the specific heats of the constituents of air. In the temperature range from 400 to 1700°R,

$$a_1 = 0.2318$$
$$b_1 = 0.104 \times 10^{-4}$$
$$c_1 = 0.7166 \times 10^{-8}$$

RATIO OF SPECIFIC HEATS

The ratio of specific heats was calculated from the expression:

$$\gamma = \frac{CP}{CP - \frac{R}{J}} \tag{I-2}$$

MACH NUMBER

At stations where both the static and total pressure were measured, the Mach number was obtained from the equation:

$$M = \sqrt{\left(\frac{2}{\gamma - 1}\right)\left[\frac{1}{\left(\frac{PS}{P}\right)^{\frac{\gamma-1}{\gamma}}} - 1\right]} \tag{I-3}$$

This equation was used to calculate the Mach number at the venturi throat when the venturi was unchoked.

VELOCITY

Velocity was determined from the relation:

$$V = \sqrt{\left(\frac{2\gamma gcRT}{\gamma-1}\right)\left[1 - \left(\frac{PS}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]} \quad , \text{ ft/sec} \tag{I-4}$$

AIRFLOW

Venturi Airflow

Airflow at station 1N (venturi throat) was measured with a critical-flow venturi and calculated as follows:

For critical flow:

$$WA1N = (P00)(A1N)(CF1N)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \sqrt{\frac{\gamma gc}{R\ T00}},\ \text{lbm/sec} \tag{I-5}$$

For subcritical flow:

$$WA1N = (PS1N)(A1N)(CF1N)\ \frac{\sqrt{\left(\frac{2gc}{R\ T00}\right)\left(\frac{\gamma}{\gamma-1}\right)\left[1 - \left(\frac{PS1N}{P00}\right)^{\frac{\gamma-1}{\gamma}}\right]}}{\left(\frac{PS1N}{P00}\right)^{\frac{\gamma-1}{\gamma}}},\ \text{lbm/sec} \tag{I-6}$$

where CF1N is an empirically determined flow coefficient based on the venturi wall curvature, area ratio, and boundary-layer development (Ref. 3). The flow coefficient was evaluated and expressed as a function of Mach number (M1N) and venturi throat Reynolds number (RE1N) as follows:

For choked venturi:

$$CF1N = 0.9790 + 0.002245 \text{ Log } RE1N \tag{I-7}$$

For unchoked venturi:

$$CF1N = 0.9790 + 0.002245 \text{ Log } RE1N - 0.0535\ (1 - M1N) \tag{I-8}$$

PRESSURE MAPPING PROGRAM

The engine inlet distortion mapping program creates a pictorial representation of the total pressure field existing at the engine inlet by the following technique: Average pressure is calculated as the arithmetic average of N equal-area-spaced total pressure readings (Fig. 6d). The program calculates the local-to-average pressure ratio at approximately 4200 discrete locations by use of linear interpolation circumferentially and second-order interpolation radially between the physical probe locations. Pressure data are extrapolated from the innermost and outermost radial pressure measurements to the centerbody and outer wall, respectively, using a second-order curve through the last three measured pressure values. Pressure ratios within specified ranges are assigned unique symbols for presentation

in a two-dimensional matrix which graphically represents the pressure profile at the measuring plane.

INITIAL SCREEN SELECTION PROGRAM

The initial screen selection program determines the porosity (or blockage) of each screen section necessary to produce a specified total pressure loss across each section.

The specified total pressure values are transposed from the simulated engine inlet to the plane of the distortion screen. This transposition is accomplished by maintaining the same circumferential location of each total pressure value at both planes and by adjusting the radial position at the screen plane such that each value is located at the centers of equal areas. Radial adjustment is required to account for the difference in flow annulus area from the simulated engine inlet plane to the plane of the distortion screen.

The locations of the specified total pressure values at the plane of the distortion screen are plotted on the screen pattern (Fig. 7b), and the values in each screen section are averaged (P2i).

The total area of each screen section (Ai) is determined from planimeter measurements of the pattern (Fig. 7b).

The porosity (S1) of one screen section is arbitrarily selected. The most convenient selection is to define the porosity for this section to be the section with the minimum blockage.

The airflow through the duct immediately downstream of the screen plane is considered to be comprised of separate flow tubes (one for each screen section) each having a unique airflow (WAi), total pressure (P2i), and flow area (Ai). The flow tubes are assumed to have the same stream static pressure (PS2) and total temperature (T2).

The airflow through each screen section (WAi) and the static pressure immediately downstream of the screen plane (PS2) are determined from a simultaneous solution of the equations:

$$\sum_{i=1}^{N} \mathrm{WAi} = \mathrm{WA1N},\ \mathrm{lbm/sec} \tag{I-9}$$

and

$$\mathrm{WAi} = \frac{\mathrm{Ai\ P2i}}{\sqrt{\mathrm{T2}}}\sqrt{\left(\frac{2gc}{R}\right)\left(\frac{\gamma}{\gamma-1}\right)\left[\left(\frac{\mathrm{PS2}}{\mathrm{P2i}}\right)^{\frac{2}{\gamma}} - \left(\frac{\mathrm{PS2}}{\mathrm{P2i}}\right)^{\frac{\gamma+1}{\gamma}}\right]},\ \mathrm{lbm/sec} \tag{I-10}$$

where

Ai = Total area of ith screen section, $in.^2$

P2i = Specified average total pressure downstream of the ith screen section, psia

T2 = Specified air total temperature, °R

PS2 = Static pressure downstream of the screen plane (assumed constant across the duct), psia

Values of PS2 are assumed, and the calculation is continued until the calculated total airflow (ΣWAi) agrees with the specified total airflow (WA1N) within ±1 percent.

The flow area of the screen section with a known porosity (AF1) is calculated from the equation:

$$AF1 = A1\,(S1)\,, \quad in.^2 \qquad \text{(I-11)}$$

where

A1 = Total area of the screen section with known porosity, $in.^2$

S1 = Screen porosity, ratio of open area to total area

The total pressure at the screen plane (PX) is assumed to be uniform across the duct and is calculated from the equation:

$$PX = \frac{PSX}{\left[\frac{PSX}{PX}\right]}\,, \quad psia \qquad \text{(I-12)}$$

where

PSX = PS2

and

PSX/PX is calculated from an iterative solution of the equation:

$$WA1 = \frac{(AF1)\,PSX}{\sqrt{T2}}\;\frac{\sqrt{\left(\frac{2gc}{R}\right)\left(\frac{\gamma}{\gamma-1}\right)\left[1-\left(\frac{PSX}{PX}\right)^{\frac{\gamma-1}{\gamma}}\right]}}{\left(\frac{PSX}{PX}\right)^{\frac{\gamma-1}{\gamma}}}\,, \quad lbm/sec \qquad \text{(I-13)}$$

where

WAi = Airflow through screen section with known flow area, lbm/sec

The flow area for each screen section (AFi) is calculated from the equation:

$$AFi = \frac{\dfrac{WAi\sqrt{T2}}{PX}}{\sqrt{\left(\dfrac{2gc}{R}\right)\left(\dfrac{\gamma}{\gamma - 1}\right)\left[\left(\dfrac{PSX}{PX}\right)^{\frac{2}{\gamma}} - \left(\dfrac{PSX}{PX}\right)^{\frac{\gamma+1}{\gamma}}\right]}}, \text{ in.}^2 \qquad \text{(I-14)}$$

The porosity of each screen section (Si) is determined from the equation:

$$Si = \frac{AFi}{Ai} \qquad \text{(I-15)}$$

SCREEN MODIFICATION PROGRAM

The calculations for the screen modification procedure use measured data to determine a total pressure loss coefficient for each screen section and use this coefficient as a basis to predict the pressure loss for a proposed replacement screen of different porosity.

The airflow for each screen section (WAi) is calculated from the equation:

$$WAi = \frac{(WA1N)(Si)(Ai)}{AFT}, \text{ lbm/sec} \qquad \text{(I-16)}$$

where

Si = Porosity of ith screen section used for the test data run

AFT = Total flow area at the screen plane, in.^{2}

The measured total pressure loss coefficient for each screen section (Cdi) is determined from the equation:

$$Cdi = \frac{P1 - P2i}{q1i} \qquad \text{(I-17)}$$

where

P1 = Measured total pressure upstream of the screen plane, psia

P2i = Measured average total pressure downstream of the ith screen section, psia

and q1i is determined from the equation:

$$q1i = \left(\frac{\gamma}{\gamma - 1}\right)\left[\frac{1}{\left(\frac{PS1i}{P1}\right)^{\frac{\gamma - 1}{\gamma}}} - 1\right]\left(\frac{PS1i}{P1}\right) P1, \text{ psi} \tag{I-18}$$

and the pressure ratio (PS1i/P1) is calculated from an iteration of the equation:

$$WAi = \frac{Ai\,(P1)}{\sqrt{T2}} \sqrt{\left(\frac{2gc}{R}\right)\left(\frac{\gamma}{\gamma - 1}\right)\left[\left(\frac{PS1i}{P1}\right)^{\frac{2}{\gamma}} - \left(\frac{PS1i}{P1}\right)^{\frac{\gamma + 1}{\gamma}}\right]}, \text{ lbm/sec} \tag{I-19}$$

An adjusted total pressure loss coefficient for each proposed screen replacement (Cdci) is calculated from the equation:

$$Cdci = Cdi \frac{\left[\frac{1 - Sci}{(Sci)^2}\right]}{\left[\frac{1 - Si}{(Si)^2}\right]} \tag{I-20}$$

where

Sci = Proposed porosity for ith screen section

The predicted total pressure loss for each proposed screen section (ΔPci) is calculated from the equation:

$$\Delta Pci = Cdci\,(q1i), \text{ psi} \tag{I-21}$$

The predicted average total pressure downstream of each screen section (P2ci) is determined from the equation:

$$P2ci = P1 - \Delta Pci, \text{ psia} \tag{I-22}$$

STANDARD DEVIATION (σ)

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left[\frac{\left(\frac{PLOCAL}{PAVG}\right)_{Meas_i}}{\left(\frac{PLOCAL}{PAVG}\right)_{Des_i}} - 1\right]^2}{N}} \tag{I-23}$$

where

$$\left(\frac{PLOCAL}{PAVG}\right)_{Meas_i} = \text{Ratio of measured local-to-average total pressure at ith probe location}$$

$$\left(\frac{PLOCAL}{PAVG}\right)_{Des_i} = \text{Ratio of desired local-to-average total pressure at ith probe location}$$

N = Number of probe locations

GENERALIZED STATIC PRESSURE FUNCTION (PSFN)

The generalized static pressure function at any axial station (d) upstream of the distortion screen is as calculated from the equation:

$$PSFN = \left[\frac{\left(\frac{PSMAX - PSMIN}{PSAVG}\right)_d}{\frac{q1}{PS1}}\right]\left[\frac{SMIN}{SMAX}\right]\left[\frac{1}{AT}\sum_{i=1}^{N}(Si)(Ai)\right] \tag{I-24}$$

where

PSMAX = Maximum static pressure at axial station d, psia

PSMIN = Minimum static pressure at axial station d, psia

PSAVG = Average static pressure at axial station d, psia

q1 = Dynamic pressure at axial station where the static pressure variation is zero, psia

PS1 = Static pressure at axial station where the static pressure variation is zero, psia

SMIN = Porosity of the most dense screen in the pattern

SMAX = Porosity of the least dense screen in the pattern

and where

$$\frac{1}{AT}\sum_{i=1}^{N}(Si)(A1) = \text{Ratio of total open area at the screen to total duct area}$$

where

AT	=	Total duct area, in.^{2}
Si	=	Porosity of individual screen section
Ai	=	Area of individual screen section, in.^{2}
N	=	Total number of individual screen sections

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13. ABSTRACT

A technique was developed for the design of distortion screens which will produce a specified steady-state total pressure profile at the inlet of a turbine engine. The design technique is discussed, and sample results of its application are presented. The influence of the distortion screens on wall static pressure upstream of distortion screens is discussed, and the total pressure distortion from a 180-deg solid plate is presented. Measured total pressure loss is presented for screens of various porosity.

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